Investigating Human Error

Incidents, Accidents, and Complex Systems

Second Edition

Barry Strauch

CRC Press
Taylor & Francis Group

Investigating Human Error

Incidents, Accidents, and Complex Systems

Second Edition

Investigating Human Error

Incidents, Accidents, and Complex Systems

Second Edition

Barry Strauch

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-1-4724-5868-1 (Paperback)

Library of Congress Cataloging-in-Publication Data

Names: Strauch, Barry, author.
Title: Investigating human error : incidents, accidents, and complex systems / Barry Strauch.
Description: Second edition. | Boca Raton : Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, [2017] | Includes bibliographical references and index.
Identifiers: LCCN 2016041252| ISBN 9781472458681 (pbk. : acid-free paper) | ISBN 9781472458650 (hardback) | ISBN 9781315589749 (ebook)
Subjects: LCSH: System failures (Engineering) | Accident investigation. | Human engineering. | Aircraft accidents--Investigation. | Aeronautics--Human factors.
Classification: LCC TA169.5 .S74 2017 | DDC 363.12/065--dc23
LC record available at https://lccn.loc.gov/2016041252

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

This book is dedicated to the memory of Howard B. Brandon, Jr.

1982–2016

Contents

Section III Sources of Data

Section IV Issues

Foreword to Second Edition

> Many accident investigations make the same mistake in defining causes. They identify the widget that broke or malfunctioned, then locate the person most closely connected with the technical failure: the engineer who miscalculated an analysis, the operator who missed signals or pulled the wrong switches, the supervisor who failed to listen, or the manager who made bad decisions. When causal chains are limited to technical flaws and individual failures, the ensuing responses aimed at preventing a similar event in the future are equally limited: they aim to fix the technical problem and replace or retrain the individual responsible. Such corrections lead to a misguided and potentially disastrous belief that the underlying problem has been solved. (Columbia Accident Investigation Board, 2003, p. 97)

I'll never forget the day my phone rang early on a Sunday morning in 2006. The voice on the other end of the line informed me there had been an airline crash in Lexington, Kentucky. The airplane was still on fire and multiple fatalities were expected. With that, I started packing my bags to head to Kentucky.

Before even leaving my house, the images on TV pretty much told me what had happened. The wreckage was positioned a few thousand feet directly off the end of a runway that would have been too short for an airplane of that size to successfully takeoff. A broken fence at the end of the runway and tire marks through the grass to the initial impact point provided further clues. So, before even leaving my house, I had surmised the pilots made an error of attempting to depart from the wrong runway.

Error identified, case closed. Right?

Well, actually not. A good friend, Captain Daniel Maurino, stated "the discovery of human error should be considered as the starting point of the investigation, and not the ending point that has punctuated so many previous investigations" (Maurino, 1997). His words of wisdom are framed in my office to serve as a constant reminder of the necessity to look behind the obvious human error. It is one thing to say someone committed an error, but it is quite another to try to identify the underlying factors that influenced that error. And why do we care? Finding who or what is at "fault" should not be simply an exercise in attributing error, but rather, should be for the purpose of identifying the factors that influenced the error so those conditions can be corrected to prevent future errors. If we simply say "human error," "pilot error," or "operator error," and stop with that, we miss valuable learning opportunities. The Institute of Medicine noted in a seminal report on medical error that "blaming the individual does not change these factors and the same error is likely to recur" (Institute of Medicine, 2000, p. 49).

In the case of the Lexington, Kentucky crash, the error was identified within hours, if not minutes, after it occurred. But, identifying the human error doesn't mean the investigation is completed; instead, it should be, as Daniel Maurino stated, the starting point of the investigation.

Once the human error was identified, the prevailing question should (and did) become "Why was the error committed?" Were the pilots fatigued? Did the fact that the airport was undergoing construction of runways and taxiways somehow confuse the pilots during taxi-out? How did the disparity between taxiway signs and what was depicted on the pilots' airport diagram charts affect their performance? Did organizational factors such as poor training or lack of company standardization somehow contribute to the error? What role did understaffing in the control tower play? Did the crew's casual attitude enable their error? Why did two other flights successfully navigate the airport construction and taxi to the correct runway in the moments before the crash, but this crew did not? Only after questions such as these are answered can the human error be understood and the underlying conditions corrected.

Since that accident in 2006, I've been involved in the deliberation of some 150 or so transportation accidents. From that experience, I have developed the belief that most, if not all, accidents or incidents have roots in human error. In some cases, it is a readily identifiable error of a frontline operator, such as a pilot, ship's master, medical technician, air traffic controller, or control room operator. In other cases, the error(s) may not be obvious at all. It may be deeply embedded within the system, perhaps far, far away from the scene of the accident, such as decisions and actions/inactions made by organizations or regulators. As explained in this book, there are proximate errors—those that are closest to the accident in terms of timing or location, and there are underlying conditions that are factors in the accident causation, but perhaps not readily apparent. Reason (1990, 1997) refers to these as active failures, and latent conditions, respectively.

Contemporary thinking views error as a "symptom of deeper trouble" (Dekker, 2002, p. 61) within the system. Maurino said human error should be "considered like fever: an indication of illness rather than its cause. It is a marker announcing problems in the architecture of the system" (Maurino, 1997).

In the early 1990s, then National Transportation Safety Board (NTSB) board member John Lauber was one of the first to focus on how organizational factors can influence transportation safety (Meshkati, 1997). Lauber argued that the cause of a commuter airliner in-flight breakup due to faulty maintenance should be "the failure of Continental Express management to establish a corporate culture which encouraged and enforced adherence to approved maintenance and quality assurance procedures" (NTSB, 1992, p. 54). Of the five NTSB board members, Lauber was alone in his belief. The conventional thinking at the time seemed to be to identify the proximate

error that sparked the accident and call that the "cause" of the mishap. But, as discussed throughout this book, human error does not occur in a vacuum. It must therefore be examined in the context in which the error occurred. In other words, if an error occurs in the workplace, the workplace must be examined to look for conditions that could provoke error. What were the physical conditions at the workplace? Was lighting adequate to perform the task? Were the procedures and training adequate? Did the organizational norms and expectations prioritize safety over competing goals? Was the operational layout of the workplace conducive for error?

Organizational factors have been implicated in accidents and incidents in many socio-technical industries. For example, the U.S. Chemical Safety and Hazard Investigation Board (Chemical Safety Board [CSB]) determined that a 2005 oil refinery explosion that claimed 15 lives and injured 180 people had numerous organizational-related factors, such as the company's cost cutting and overreliance on misleading safety metrics (CSB, 2007). The International Atomic Energy Agency (IAEA) stated that the Chernobyl nuclear power plant meltdown "flowed from a deficient safety culture, not only at the Chernobyl plant, but throughout the Soviet design, operating, and regulatory organizations for nuclear power" (IAEA, 1992, pp. 23–24). The National Transportation Safety Board (2010) found organizational issues to be a causal factor in the 2009 multi-fatality subway accident in Washington, DC.

In 2015, I was involved in the final deliberation of an accident involving SpaceShipTwo, a commercial space vehicle that suffered an in-flight breakup during a test flight. From the onboard video recorder, it was evident that the copilot prematurely moved a lever which led to an uncommanded movement of the vehicle's tail feather—a device similar to a conventional aircraft's horizontal and vertical stabilizer. The tail feather is actuated by a cockpit lever to pivot it upward 60° relative to the longitudinal axis of the aircraft; its purpose is to stabilize the aircraft during the reentry phase of flight. However, if the feather is deployed at the wrong time, as in this case, the resulting aerodynamic loads on the aircraft will lead to catastrophic in-flight breakup. The obvious "cause" of the accident was that the copilot committed an error of unlocking the feather at the wrong time which led to the uncommanded actuation of the feather. But, this finding alone would serve no useful purpose for preventing similar errors in the future. After all, the copilot was killed, so surely he would not commit this error again.

By digging deeper, the investigation found that influencing the copilot's error was the high workload he was experiencing during this phase of flight, along with time pressure to complete critical tasks from memory—all while experiencing vibration and *g*-loads that he had not experienced recently. On the broader perspective, the spaceship designer/manufacturer, Scaled Composites, did not consider that this single error could lead to an unintended feather activation. Although the copilot had practiced for this flight several times in the simulator, this premature movement

of the feather unlock lever occurred on the fourth powered flight of the SpaceShipTwo, indicating to me that the likelihood of this error was high. "By not considering human error as a potential cause of uncommanded feather extension of the SpaceShipTwo, Scaled Composites missed opportunities to identify the design and/or operational requirements that could have mitigated the consequences of human error during a high workload phase of flight" (NTSB, 2015, p. 67). Because of the underlying design implications, the National Transportation Safety Board issued a safety recommendation to the Federal Aviation Administration (FAA) to ensure that commercial space flight entities identify and address "single flight crew tasks that, if performed incorrectly or at the wrong time, could result in a catastrophic hazard" (NTSB, 2015, p. 70). In addition, the manufacturer added a safety interlock to ensure that this lever could not be activated during this critical flight regime.

Not only can organizations create error provoking conditions, but regulators can do so as well. Examples include failing to provide adequate oversight and enforcement, or not developing adequate procedures. In 2009, a Pacific Gas & Electric Company (PG&E) 30-inch diameter natural gas transmission pipeline ruptured and exploded. The conflagration claimed eight lives in San Bruno, California, destroyed 38 homes and damaged 70. The investigation determined that oversight and enforcement by both the state and federal regulators was ineffective, which "permitted PG&E's organizational failures to continue over many years" (NTSB, 2011, p. 126).

So, as you can see, human behavior, including errors, can be influenced by many factors. Therefore, investigation of human error should not be a random hit or miss process. It should be conducted in an organized, methodical process, with a clear purpose in mind. Dr. Barry Strauch has been on the frontlines of investigating human error for nearly 35 years and he has provided human factors expertise to well over a hundred aviation and maritime accidents. Between the covers of this book, he lays out in clear terms the factors that enable human error, including individual factors such as fatigue, stress, and medical factors. He also examines in detail organizational and regulatory precursors to error. Each chapter provides a bulleted checklist to facilitate identifying relevant factors. This second edition provides an update to what I found to be an excellent reference—one that I often referred to in my decade of serving on an accident investigation board, as indicated by scores of dog-eared pages filled with underlining and highlighting. I encourage anyone involved with investigating any type of error—whether that error occurred in the hospital, on the hangar floor, in a nuclear control room, or on the flight deck of an airliner—to use this text as resource to investigating human error. Using this book as a guide—I assure you—will not be an error.

Robert L. Sumwalt
Washington, DC

References

Chemical Safety Board. 2007. Investigation report: Refinery explosion and fire. BP, Texas City, TX. CSB Report No. 2005-04-I-TX. Washington, DC: Chemical Safety Board.

Columbia Accident Investigation Board. 2003. *Columbia accident investigation board report (Vol. 1)*. Washington, DC: Columbia Accident Investigation Board.

Dekker, S. 2002. *The field guide to human error investigations*. Aldershot, England: Ashgate Publishing International.

Institute of Medicine. 2000. *To err is human: Building a safer health system*. Washington, DC: National Academy Press.

International Atomic Energy Agency. 1992. *The Chernobyl accident: Updating of INSAG-1. A Report by the International Nuclear Safety Advisory Group. Safety Series 75-INSAG-7*. Vienna: International Atomic Energy Agency. Retrieved http://www-pub.iaea.org/MTCD/publications/PDF/Pub913e_web.pdf

Maurino, D. E. 1997. Aviation human factors and the safety investigation process. Paper presented at ISASI 1997 International Air Safety Conference, Anchorage, AK.

Meshkati, N. 1997. Human performance, organizational factors and safety culture. National Transportation Safety Board Symposium on Corporate Culture in Transportation Safety, April, Arlington, VA.

National Transportation Safety Board. 1992. Aircraft accident report: Britt Airways, Inc., d/b/a Continental Express Flight 2574 In-Flight Structural Breakup, EMB-120RT, N33701, Eagle Lake, Texas, September 11, 1991. Report No. AAR/92-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2010. Railroad accident report. Collision of two Washington Metropolitan Area Transit Authority Metrorail Trains Near Fort Totten Station, Washington, DC, June 22, 2009. Report No. RAR-10/02. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2011. Pipeline accident report. Pacific Gas and Electric Company, Natural Gas Transmission Pipeline Rupture and Fire, San Bruno, California, September 9, 2010. Report No. PAR-11/01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2015. Aircraft accident report. In-Flight Breakup during Test Flight, Scaled Composites SpaceShipTwo, N339SS Near Koehn Dry Lake, California, October 31, 2014. Report No. AAR-15/02. Washington, DC: National Transportation Safety Board.

Reason, J. T. 1990. *Human error*. Cambridge, England: Cambridge University Press.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate Publishing International.

Reiman, T. and C. Rollenhagen. 2011. Human and organizational biases affecting the management of safety. *Reliability Engineering and System Safety*, 96 (10), 1263–1274. doi: 10.1016/j.ress.2011.05.010

Foreword to First Edition

Like the rest of the modern world, I owe an enormous debt to the skills of professional accident investigators. As a traveler and a consumer, I am extremely grateful for what they have done to make complex technologies significantly safer; but as an academic, I have also been especially dependent on their published findings. Although, mercifully, I have had very little first-hand experience of the real thing, this has not prevented me from writing, lecturing, and theorizing about the human contribution to the breakdown of complex systems for the past 30 years or so. There are perhaps two reasons why I have so far been able to pull this off. The first is that the ivory tower provided the time and resources to look for recurrent patterns in a large number of adverse events over a wide range of hazardous technologies, a luxury that few "real-world" people could enjoy. The second has been the high quality of most major accident reports. If such accounts had later been shown to lack accuracy, insight, analytical depth, or practical value, then my reliance upon them would have been foolish or worse. But while many have challenged the theories, very few have questioned the credibility of the sources.

So, you might ask, if accident investigators are doing so well, why do they need this book? The most obvious answer is that human, organizational, and systemic factors, rather than technical or operational issues, now dominate the risks to most hazardous industries—yet the large majority of accident investigators are technical and operational specialists. Erik Hollnagel (1993) carried out a survey of the human factors literature over three decades to track the increasing prominence of the "human error" problem. In the 1960s, erroneous actions of one kind or another were estimated as contributing around 20% of the causal contributions to major accidents. By the 1990s, however, this figure had increased fourfold. One obvious explanation is that the reliability of mechanical and electronic components has increased markedly over this period, while complex systems are still being managed, controlled, and maintained by Mark I human beings.

In addition, this period has seen some subtle changes in the way we perceive the "human error" problem and its contribution to accidents. For the most part, "human error" is no longer viewed as a single portmanteau category, a default bin into which otherwise unexplained factors can be dumped. We now recognize that erroneous actions come in a variety of forms and have different origins, both in regard to the underlying psychological mechanisms and their external shaping factors. It is also appreciated that frontline operators do not possess a monopoly on error. Slips, lapses, mistakes, and violations can occur at all levels of the system. We are now able to view errors as consequences rather than sole causes, and see frontline operators

more as the inheritors rather than the instigators of accidents in complex systems.

System complexity derives in large part from the existence of diverse and redundant layers of defences, barriers, and safeguards that are designed to prevent operational hazards from coming into damaging contact with people, assets, and the environment. The nuclear industry calls them "defenses-in-depth." Such characteristics make it highly unlikely that accidents in complex systems arise from any single factor, be it human, technical, or environmental. The apparently diabolical conjunction of several different factors is usually needed to breach all of these defenses-in-depth at the same time. This makes such events less frequent, but the causes more complex. Some of the latent contributions have often lain dormant in the system for many years prior to the accident. Given the increasing recognition that contributing factors can have both a wide scope and a long history, it is almost inevitable that investigators will net larger numbers of human and organizational shortcomings.

Another associated change—at least within the human factors and investigative communities—has been a shift away from the "person model" of human error, in which the search for causes and their countermeasures is focused almost exclusively upon the psychology of individuals. Instead, there has been an increasing willingness to take a systems view of accident causation in which the important question is not "Who blundered?" but "How and why did the defenses fail?" Unfortunately, the person model is still deeply embedded in the human psyche, and is especially pernicious in its moral (or legal) form. This is the widespread belief that responsible and highly trained professionals (pilots, surgeons, ship's officers, control room operators, and the like) *should not* make errors. However, when such erroneous actions do occur, it is assumed that they are *sufficient* to cause bad accidents. The reality, of course, is quite different. Highly trained, responsible professionals make frequent errors, but most are inconsequential, or else they are detected and recovered (see, e.g., Amalberti and Wioland, 1997). Moreover, these errors are only occasionally *necessary* to add the final touches to an accident-in-waiting, a potential scenario that may have been lurking within a complex system for a long time.

The achievements of accident investigators are all the more remarkable when one considers the snares, traps, and pitfalls that lie in their path. Aside from the emotional shock of arriving at often inaccessible and hostile locations to confront the horrors of an accident site, investigators are required to track backward—sometimes for many years—in order to create a coherent, accurate, and evidence-based account of how and why the disaster occurred, and to make recommendations to prevent the recurrence of other tragedies. The first and most obvious problem is that the principal witnesses to the accident are often dead or incapacitated. But this, as most investigators would acknowledge, goes with the territory. Other difficulties are less apparent and have to do with unconscious cognitive biases that influence the way people

arrive at judgments about blame and responsibility and cause and effect. While human factors specialists have focused mainly upon the error tendencies of the operators of complex systems, there has also been considerable interest in how people trying to make sense of past events can go astray. Let me briefly review some of these investigative error types. They fall into two related groups: those that can bias attributions of blame and responsibility and those that can distort perceptions of cause and effect.

Here are some of the reasons why the urge to blame individuals is so strong. When looking for an explanation of an occurrence, we are biased to find it among human actions that are close in time and place to the event, particularly if one or more of them are considered discrepant. This leads to what has been termed the *counterfactual fallacy* (Miller and Turnbull, 1990) where we confuse what might have been with what ought to have been, particularly in the case of bad outcomes. The fallacy goes as follows: Had things been otherwise (i.e., had this act not happened), there would have been no adverse result; therefore, the person who committed the act is responsible for the outcome.

Another factor that leads to blaming is the *fundamental attribution error* (Fiske and Taylor, 1984). This is the universal human tendency to resort to dispositional rather than to situational influences when explaining people's actions, particularly if they are regarded as unwise or unsafe. We say that the person was stupid or careless; but, if the individual in question were asked, he or she is most likely to point to the local constraints. The truth usually lies somewhere in between.

The *just world hypothesis* (Lerner, 1970)—the view that bad things happen to bad people, and conversely—comes into play when there is an especially unhappy outcome. Such a belief is common among children, but it can often last into adulthood. A close variant is the *representativeness heuristic* (Tversky and Kahneman, 1974) or the tendency to presume a symmetrical relationship between cause and effect—thus bad consequences must be caused by horrendous blunders, while particularly good events are seen as miracles.

Yet another reason why people are so quick to assign blame is the *illusion of freewill* (Lefcourt, 1973). People, particularly in western cultures, place great value in the belief that they are the controllers of their own fate. They can even become mentally ill when deprived of this sense of personal freedom. Feeling themselves to be capable of choice naturally leads them to assume that other people are the same. They are also seen as free agents, able to choose between right and wrong, and between correct and erroneous actions. But our actions are often more constrained by circumstances than we are willing to admit or understand.

All accident investigators are faced with the task of *digitizing* an essentially analog occurrence; in other words, they have to chop up continuous and interacting sequences of prior events into discrete words, paragraphs, conclusions, and recommendations. If one regards each sequence as a piece of

string (though it is a poor analogy), then it is the investigator's task to tie knots at those points marking what appear to be significant stages in the development of the accident. Such partitioning is essential for simplifying the causal complexity, but it also distorts the nature of the reality (Woods, 1993). If this parsing of events correctly identifies proper areas for remediation, then the problem is a small one; but it is important for those who rely on accident reports to recognize that they are—even the best of them—only a highly selected version of the actuality, and not the whole truth. It is also a very subjective exercise. Over the years, I have given students the task of translating these accident narratives into event trees. Starting with the accident itself, they were required to track back in time, asking themselves at each stage what factors were necessary to bring about the subsequent events—or, to put it another way, which elements, if removed, would have thwarted the accident sequence. Even simple narratives produced a wide variety of event trees, with different nodes and different factors represented at each node. While some versions were simply inaccurate, most were perfectly acceptable accounts. The moral was clear: the causal features of an accident are to the analyst what a Rorschach test (inkblot test) is to the psychologist—something that is open to many interpretations. The test of a good accident report is not so much its fidelity to the often-irrecoverable reality, but the extent to which it directs those who regulate, manage, and operate hazardous technologies toward appropriate and workable countermeasures.

A further problem in determining cause and effect arises from the human tendency to confuse the present reality with that facing those who were directly involved in the accident sequence. A well-studied manifestation of this is *hindsight bias* or the *knew-it-all-along effect* (Fischhoff, 1975; Woods et al., 1994). Retrospective observers, who know the outcome, tend to exaggerate what the people on the spot should have appreciated. Those looking back on an event see all the causal sequences homing in on that point in time at which the accident occurred; but those involved in the prior events, armed only with limited foresight, see no such convergence. With hindsight, we can easily spot the indications and warning signs that should have alerted those involved to the imminent danger. But most "warning" signs are only effective if you know in advance what kind of accident you are going to have.

Sydney Decker (2001) has added two further phenomena to this catalog of investigative pitfalls: he termed them *micro-matching* and *cherry-picking*. Both arise, he argues, from the investigator's tendency to treat actions in isolation. He calls this "the disembodiment of human factors data." *Micro-matching* is a form of hindsight bias in which investigators evaluate discrete performance fragments against standards that seem applicable from their after-the-fact perspective. It often involves comparing human actions against written guidance or data that were accessible at the time and should have indicated the true situation. As Decker puts it: "Knowledge of the 'critical' data comes only with the omniscience of hindsight, but if data can be shown to have been physically available, it is assumed that it should have been picked up by

the practitioners in the situation." The problem, he asserts, is that such judgments do not explain why this did not happen at the time. *Cherry-picking*, another variant of hindsight bias, involves identifying patterns of isolated behavioral fragments on the basis of post-event knowledge. This grouping is not a feature of the reality, but an artifact introduced by the investigator. Such tendencies, he maintains, derive from the investigator's excessive reliance upon inadequate folk models of behavior, and upon human reactions to failure. Fortunately, he outlines a possible remedy "in the form of steps investigators can take to reconstruct the unfolding mindset of the people they are investigating, in parallel and tight connection with how the world was evolving around these people at the time."

Clearly, accident investigators need help in making sense of human factors data. But I am not sure that Olympian pronouncements (or even Sinaian tablets) are the way to provide it, nor am I convinced that investigators can ever "reconstruct the unfolding mindset of the people they are investigating"—I can't even construct my present mindset with any confidence. This book, on the other hand, delivers the goods in a way that is both useful and meaningful to hard-pressed accident investigators with limited resources. It is well written, well researched, extremely well informed, and offers its guidance in a down-to-earth, practical, and modular form (i.e., it can be read via the contents page and index rather than from cover to cover). It is just the thing, in fact, to assist real people doing a vital job. And, as far as I know, there is nothing else like it in the bookshops.

James Reason

References

Amalberti, R. and L. Wioland. 1997. Human error in aviation. In H. M. Soekkha (Ed.), *Aviation safety*, pp. 91–108. Utrecht, The Netherlands: VSP.

Decker, S. W. A. 2001. The disembodiment of data in the analysis of human factors accidents. *Human Factors and Aerospace Safety*, 1: 39–58.

Fischhoff, B. 1975. Hindsight is not foresight: The effect of outcome knowledge on judgement under uncertainty. *Journal of Experimental Psychology: Human Perception and Performance*, 1: 288–299.

Fiske, S. T. and S. E. Taylor. 1984. *Social cognition*. Reading, MA: Addison-Wesley.

Hollnagel, E. 1993. *Human reliability analysis: Context and control*. London: Academic Press.

Lefcourt, H. M. 1973. The function of illusions of control and freedom. *American Psychologist*, May, 417–425.

Lerner, M. J. 1970. The desire for justice and the reaction to victims. In J. McCauley and I. Berkowitz (Eds.), *Altruism and helping behavior*, pp. 205–229. NY: Academic Press.

Miller, M. W. and W. Turnbull. 1990. The counterfactual fallacy: Confusing what might have been with what ought to have been. *Social Justice Research*, 4: 1–9.

Tversky, A. and D. Kahneman. 1974. Judgment under uncertainty: Heuristics and biases. *Science*, 185: 1124–1131.

Woods, D. D. 1993. Process tracing methods for the study of cognition outside of the experimental laboratory. In G. A. Klein, J. Orasunu, R. Calderwood, and C. E. Zsambok (Eds.), *Decision making in action: Models and methods*, pp. 228–251. Norwood, NJ: Ablex.

Woods, D. D., L. J. Johannesen, R. I. Cook, and N. B. Sarter. 1994. *Behind human error: Cognitive systems, computers and hindsight*. Dayton, OH: CSERIAC.

Preface to Second Edition

I have seen many changes in the understanding of human error as well as in the role that it plays in accident causation in the 15 years since this book was first published. In that time, considerable research has been conducted in such areas as automation, team performance, safety management, and fatigue, research that has given investigators additional knowledge with which to assess the causes of human error. In this interval, we have also witnessed a worldwide decline in major aircraft accidents. Unfortunately, some of the accidents that have occurred since then appear to have been influenced by the same antecedents to error that we have seen all too frequently over the years. For example, the accident used in the case study in Chapter 16, while more current and with more complex errors than was true of the case study in the first edition, illustrates automation-related errors that are almost identical to those seen in previous accidents, including one committed almost 30 years earlier. Because people and the systems they operate do not always learn from their mistakes, the need for thorough and systematic human factors investigations of error becomes that much more critical. Hopefully, the lessons to be learned from these investigations can be used to avoid further accidents.

Not only have operators continued to make errors that have led to accidents, but mishaps in which the antecedents were well known but ignored have occurred in other systems as well. For example, the case of Bernard Madoff, whose Ponzi scheme cost many investors their life savings, illustrates how ineffective oversight can exacerbate system errors. The U.S. regulator of financial securities had been informed of the Madoff Ponzi scheme well before the scheme was exposed, yet nothing was done to stop him, despite its own (flawed) investigation and the presence of publicly available information that could have pointed out the fraud. The regulator did not cause the scheme, but by failing to properly oversee the financial system in which it operated, it contributed to losses of millions of investor dollars beyond what would have been the case had it acted effectively when it initially learned of the scheme.

In the years since the first edition, we have also witnessed the world's third major civilian nuclear reactor accident, the March 2011 meltdown in the Fukushima Daiichi nuclear generating plant in Japan. A reactor core melted after coolant ceased flowing to it, following flooding of the backup diesel generators, a result of a devastating tsunami. Because the plant was located in a seismic zone, near the ocean, it was potentially prone to tsunamis. Regulators therefore required protection against them. In addition to building a seawall, designers had installed backup generators to enable coolant to be pumped to the core in the event that primary power was lost.

However, although backup generators were required and installed, designers and regulators failed to consider the possibility of a tsunami of sufficient magnitude that would exceed the seawall limits and flood the backup generators, which had been placed at ground level behind the seawall. In this manner, designers, regulators, operators, and all who play integral roles in complex systems, have continued to create antecedents to errors that appear, in hindsight, to have been preventable.

While this book does not attempt to provide foresight to those designing or operating complex systems, I do hope that it will provide knowledge needed to effectively investigate the results of their errors to identify their antecedents. Because of the findings of both accident investigations and of the human factors research conducted in the interim, we have a better understanding of error causation than we did 15 years ago. We know more, for example, than we did then about automation's effects on operators, on how fatigue can adversely affect cognitive performance, and how organizations can contribute to operator errors and the research cited in this text reflects these advances.

My experience as an investigator, with now over 30 years of conducting error investigations in major modes of transportation, has reinforced my belief that error investigators need to be aware of basic human factors research findings. The ability to identify necessary data, along with interviewing and analytical skills, are all necessary. But without an understanding of human error even the most skilled investigators will have difficulty explicating the error causation in the accidents they investigate.

In the first edition, I suggested that accident investigation is a special calling and my experience since then has only reinforced that view. To be able to understand and identify errors in a way that is constructive, and that can be used to prevent accidents, is indeed a privilege. I hope that you will find this text helpful and contributing to your own endeavors. Should you investigate an accident, I hope that you will make a positive contribution to safety by helping to reduce its likelihood in the future.

Finally, this book is dedicated to the memory of Howard B. Brandon, Jr., whose father has been a colleague, mentor, and friend. May Howard rest in peace.

Barry Strauch
Annandale, Virginia

Preface to First Edition

From the time I was a boy growing up in Brooklyn, I have been fascinated with New York's subway system. When I was 11, I began a tradition that lasted 3 years. To celebrate the last day of school, I would ride at the head end of a subway train on a route that I had not taken before. I never told my parents. I doubt they would have understood. I loved the subways and riding at the very front of the train allowed me to see not only the track ahead but also to watch the operator, then called the motorman. I would stand there for hours, fascinated watching the train's movements and the train operator as he would move the train forward and then slow it down and stop it at each station.

From these beginnings, my interest in complex systems and especially transportation systems has grown. I later became fascinated with another system, aviation, and I tried to learn as much as I could about that field. After completing graduate school, I indulged myself by learning to fly. I became hooked. All of my free time and disposable income went to pay for lessons and flight time. After several years, I was fortunate that I could afford to acquire several pilot ratings. I even briefly considered trying to become an airline pilot. However, the airlines weren't hiring many pilots in those days and I had to enter the field another way. I became an accident investigator with the National Transportation Safety Board (NTSB).

I joined the NTSB as a human performance investigator in 1983, with several other young human factors professionals. We were among the first at the agency, or anywhere for that matter, to systematically examine the role of operator error in accidents in complex systems. They wanted us to provide more insight into the cause of an accident than to attribute it solely to operator error, the standard practice of the day.

The NTSB was, and is, a special place. Its investigators are thoroughly dedicated to its mission—to learn what causes an accident in order to prevent future accidents. Often at considerable personal sacrifice, they travel to inhospitable locales and work under great stress, to get to the bottom of terrible tragedies.

In those days, there wasn't much to guide us beyond the standard human factors design texts. Researchers at NASA Ames had been actively engaged in studying team errors and crew resource management for several years, but the fruits of their efforts would still be several years away. The Danish researcher Jens Rasmussen, and the British researchers James Reason, Neville Moray, and their colleagues in Europe were just beginning to examine error as a systems construct, after the nuclear accident at Three Mile Island. Elsewhere, the field of human error was only just beginning to emerge as a field worthy of extensive study in and of itself.

Much has happened to the field of human error since 1983, and to me as well. I have held a variety of positions at the NTSB, all related to either investigating or training others to investigate error, in both the United States and abroad. I have met many involved in transportation safety, all as dedicated and committed as my colleagues at the NTSB. But many have asked the same question—given the prominence of human error in the cause of accidents, is there anything written on how to investigate error? Unfortunately, I would have to answer that, although there was much written on error, little was available to explain how to investigate it.

I wrote this text to remedy that situation. I have based it not on any formal method that the NTSB has adopted, but on my own reading, experience, and belief in what works. It is intended for those who are interested in human error and for those who investigate errors in the course of an incident or accident investigation.*

I am indebted to many people who have helped me along the way and without whose help this text would not have been possible. Although I cannot name them all, I would like to thank several whose assistance was invaluable. Dr. Michael Walker, of the Australian Transportation Safety Bureau, commented on the organization of the text when it was still in its formative stage. Drs. Evan Byrne and Bart Elias of the National Transportation Safety Board provided beneficial comments and suggestions on an early draft. Dr. Douglas Wiegmann, of the University of Illinois, took time out from his schedule to review a draft and his comments are greatly appreciated. The questions that Dr. John Stoop, of the Delft University of Technology in the Netherlands, raised were incisive and helped guide my thinking on subsequent drafts. Dr. Mitchell Garber, the medical officer of the National Transportation Safety Board, meticulously read and offered suggestions on several drafts. His guidance went well beyond medical and human factors issues and greatly improved both the content and structure of the text. My editor, Ms. Joanne Sanders-Reio, worked with me to arrange my thoughts and more important, helped to refine and organize the text. Carol Horgan reviewed the final draft for clarity. My publisher, John Hindley provided ongoing support and encouragement from the beginning. Professor James Reason provided invaluable encouragement in these efforts.

I am especially indebted to my wife Maureen, my son Sean, and my daughter Tracy. They have put up with the over three and half years that I have spent on this project, with the attendant absences from their lives and frustrations these efforts produced. Without their patience and encouragement this book would not have been possible.

* The text reflects my views and opinions, and not necessarily those of the National Transportation Safety Board.

Finally, although he passed away over two decades ago, my father, Samuel A. Strauch, encouraged and supported a quest for learning that has remained with me to this day. This book is dedicated to his memory.

Barry Strauch
Annandale, Virginia

Author

Barry Strauch retired from the National Transportation Safety Board after over 30 years of investigating human error involved accidents in all major transportation modes, from Boeing 747 crashes to pipeline ruptures to collisions at sea involving nuclear submarines. In addition, he was on the faculty of the University of Louisville, at Embry-Riddle Aeronautical University, where he taught psychology and conducted human factors research in aviation, and he has been an adjunct faculty member in the Psychology Department of George Mason University (Arlington, Virginia). He has published papers on transportation accidents in journals such as *Safety Science and Human Factors*. He also has a pilot and an instructor pilot's license.

1

Introduction

> The ValuJet accident continues to raise troubling questions—no longer about what happened but about why it happened, and what is to keep something similar from happening in the future. As these questions lead into the complicated and human core of flight safety, they become increasingly difficult to answer.
>
> **Langewiesche, 1998**
> *The Atlantic Monthly*

Introduction

"To err is human" it is said, and people make mistakes—it is part of the human condition. When people err, they may be embarrassed or angry with themselves, but most often the errors are minor and little attention is paid to the consequences. However, sometimes the errors lead to more serious consequences. Occasionally, people working in hospitals, airlines, power stations, chemical refineries, or similar settings commit errors–errors that may cause accidents with catastrophic consequences, potentially leading to injury or death to those who played no part in the error.

Such work settings, known as "complex systems" (Perrow, 1999), generate electricity, refine crude oil, manage air traffic, transport products and people, and treat the sick, to name a few. They have brought substantial benefits to our way of life, and permitted a standard of living to which many have become accustomed, but when someone who works in these systems makes an error, the consequences may be severe. Although companies and their regulators typically establish extensive performance standards to prevent errors, these errors, which in other environments may be inconsequential, can, in these settings, result in severe consequences.

A new catastrophe seems to occur somewhere in the world with regularity, often one that is later attributed to someone doing something wrong. Whether it is an airplane accident, a train derailment, a tanker grounding, or any of the myriad events that seem to occur with regularity, the tendency of often simple errors to wreak havoc continues. Despite the progress made,

systems have not yet been developed that are immune to the errors of those who operate them. The human genetic structure has been mapped, the Internet developed, and cell phones designed with more computing power than most computers had but a few short years ago, but human error has not yet been eliminated from complex systems.

However, while error has not been eliminated, our understanding of the causes of errors has increased. Particularly in complex systems where there is little tolerance for errors, regulators, system designers, and operators have developed and implemented techniques that anticipate and address potential opportunities for error and it is hoped, prevent errors from being committed that can jeopardize system safety.

The Crash of ValuJet Flight 592

To illustrate how even simple errors can lead to a catastrophic accident, let us look at an event in one of our safest complex systems—commercial air transportation. Despite numerous measures that had been developed to prevent the very types of errors that occurred, several people, including some who were not even involved in the conduct of the accident flight, committed critical errors that led to an accident.

On May 11, 1996, just minutes after it had taken off from nearby Miami, Florida, a McDonnell Douglas DC-9 crashed into the Florida Everglades (National Transportation Safety Board, 1997). Investigators determined that the cause of the accident was relatively simple and straightforward; an intense fire broke out in the airplane's cargo compartment and within minutes burned through the compartment into the cabin, quickly spreading through the cabin. The pilots were unable to land before the fire degraded the airplane's structural integrity. All onboard were killed in the accident (Figure 1.1).

The investigation led to considerable worldwide media attention. As with any large-scale event involving a substantial loss of life, this was understandable. But other factors played a part as well. The airline had been operating for less than 3 years, and it had employed what were then nontraditional airline practices. It had expanded rapidly, and in the months before the accident experienced two nonfatal accidents. After this accident, many criticized the airline, questioning its management practices and its safety record. Government officials initially defended the airline's practices, but then reversed themselves. Just over a month after the accident, government regulators, citing deficiencies in the airline's operations, forced it to suspend operations until it could satisfy their demands for reform. This led to even more media attention.

FIGURE 1.1
The ValuJet accident site in the Florida Everglades. (Courtesy of the National Transportation Safety Board, 1997.)

As details about the crash emerged and more was learned, the scope of the tragedy increased. Minutes after takeoff, the pilots had declared an emergency, describing smoke in the cockpit. Within days investigators learned that despite strict prohibitions, canisters of chemical oxygen generators had been loaded onto the aircraft. It was believed that the canisters, the report of smoke in the cockpit, and the accident were related.

Oxygen generators provide oxygen to airline passengers in the event of a cabin depressurization and are therefore designed to be safely transported in aircraft, provided the canisters are properly installed within protective housings. However, if the canisters are not packaged properly, or are shipped without locks to prevent initiation of oxygen generation, they could inadvertently generate oxygen. The process creates heat as a by-product, bringing the surface temperature of the canisters to as high as 500°F (260°C).

Investigators believed that boxes of canisters that lacked locks or other protection were placed loosely in boxes and loaded into the airplane's cargo hold underneath the cabin. After being jostled during takeoff and climb out, the canisters began generating oxygen. The canister surfaces became heated to the point that adjacent material in the cargo compartment was ignited and a fire began. The canisters then fed the fire with pure oxygen, producing one of extraordinary intensity that quickly penetrated the fire resistant material lining the cargo hold, material that had not been designed to protect against an oxygen-fed fire. The fire burned through the cabin floor and, with the pure oxygen continuing to feed it, grew to the point where the structure weakened and the airplane become uncontrollable. It crashed into the

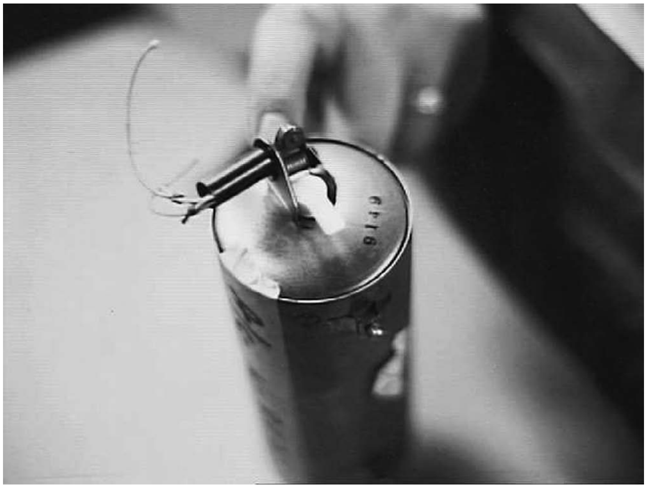

FIGURE 1.2
Unexpended, unburned chemical oxygen generator, locking cap in place, but open. (Courtesy of the National Transportation Safety Board, 1997.)

Everglades, a body of shallow water, becoming submerged under its soft silt floor (Figure 1.2).

Because of the potential danger that unprotected oxygen generators pose, they are considered hazardous and airlines are prohibited from loading unexpended and unprotected canisters of oxygen generators onto aircraft. Yet, after the accident, it was clear that someone had placed the canisters on the airplane. As a result, a major focus of the investigation emerged to determine how and why the canisters were loaded onto the airplane.

Investigators learned that no single error led to loading the canisters onto the aircraft. To the contrary, about 2 months before the accident, several individuals committed relatively insignificant errors, in a particular sequence. Each error, in itself, was seemingly minor—the type that people may commit when rushed, for example. Rarely do these errors cause catastrophic consequences. However in this accident, despite government-approved standards and procedures designed and implemented to prevent them, people still committed critical errors that resulted in a maintenance technician shipping three boxes of unexpended oxygen generators on the accident airplane.

Although the errors may have appeared insignificant, a complex system such as commercial aviation has little room for even insignificant errors. Investigators seeking to identify the errors to determine their role in the cause of the accident faced multiple challenges. Many specialists had to methodically gather and examine a vast amount of information, then analyze it to identify the critical errors, the persons who committed them, and the context in which the errors occurred.

It took substantial effort to understand the nature of the errors that led to this accident, and investigators succeeded in learning how the errors were committed. The benefits of their activities were as substantial. By meticulously collecting and analyzing the necessary data, investigators were able to learn what happened and why—information that managers and regulators then applied to system operations to make them safer. Many learned lessons from this accident, and they applied what they learned to their own operations. While the tragedy of the accident cannot be diminished, it made the aviation industry a safer one; it has not witnessed a similar type of accident. This is the hope that guides error investigations, that circumstances similar to the event being investigated will not recur and that those facing the same circumstances will not repeat the errors made earlier.

Investigating Error

Today, in many industrialized countries, government agencies or commissions generally investigate major incidents and accidents. Some countries have established agencies that are dedicated to that purpose. For example, the National Transportation Safety Board in the United States, the Transportation Safety Board of Canada, and the Australian Transport Safety Bureau, investigate incidents and accidents across transportation modes in their respective countries. In other countries, government agencies investigate accidents in selected transportation modes, such as the Air Accidents Investigation Branch of Great Britain and the BEA (Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile) of France, which investigate commercial aviation accidents and incidents.

However, when relatively minor accidents or incidents occur, organizations with little, if any, experience may need to conduct the investigations themselves. Without the proper understanding, those investigating error may apply investigative procedures incorrectly or fail to recognize how the error came about. Although researchers have extensively examined error (e.g., Reason, 1990, 1997; Woods, Johannesen, Cook, and Sarter, 1994), there is little available to guide those wishing to investigate error. Despite the many accidents and incidents that are caused by operator error, it appears that few know a formal process to investigate errors or how to apply such a method during the course of an investigation.

This book presents a method of investigating errors believed to have led to an accident or incident. It can be applied to error investigations in any complex system, although most of the examples presented are aviation related. This primarily reflects the long tradition and experience of agencies that investigate aviation accidents, and the author's experience participating in such investigations. Please consider the examples presented as tools to

illustrate points made in the book and not as reflections on the susceptibility of any one system or transportation mode to incidents or accidents. Neither the nature of the errors nor the process of investigating errors differs substantially among systems.

This book is designed for practitioners and investigators, as well as for students of error. It is intended to serve as a roadmap to those with little or no experience in human factors or in conducting error investigations. Though formal training in human factors, psychology, or ergonomics, or experience in formal investigative methodology is helpful, it is not required. The ability to understand and effectively apply an investigative discipline to the process is as important as formal training and experience.

Chapters begin with reviews of the literature and, where appropriate, follow with explicit techniques on documenting data specific to the discussion in that chapter. Most chapters also end with "helpful techniques," designed to serve as quick investigative references.

Outline of the Book

The book is divided into five sections, each addressing a different aspect of error in complex systems. Section I defines concepts that are basic to the book, errors and complex systems, Section II focuses on types of antecedents to error, Section III describes data sources and analysis techniques, Section IV discusses three contemporary issues in human error, and Section V reviews an accident in detail and presents thoughts on selected issues important to error investigations.

Chapter 2 defines error in complex systems and introduces such critical concepts as operator, incident, accident, and investigation. Contemporary error theories are discussed, with particular attention devoted to Perrow's description of system accidents (1999) and Moray (2000) and Reason's (1990, 1997), models of error in complex systems. Changes in views of error over the years are discussed.

Chapter 3 discusses the analysis of data obtained in a human error investigation. Different types of analyses are described and their relationship to human error explored. A hypothetical illustration of the application of the analysis methodology to an accident involving human error is presented, with the logic involved in each of the steps examined.

Chapter 4 begins the focus on antecedents to error by examining the role of equipment in creating error antecedents, the source of much of the early scientific work in the field of human factors. Information display and control features that affect operator performance are discussed and illustrations of their relationship to operator errors in selected accidents are presented.

Chapter 5 discusses antecedents pertaining to the system operator, historically the primary focus of those investigating error. Behavioral and physiological antecedents to error are examined, and antecedents that are operator-initiated or caused are differentiated from company-influenced antecedents.

Chapter 6 reviews antecedents pertaining to companies that operate complex systems. These antecedents incorporate many that are discussed in earlier chapters, including operating procedures and company oversight of the application of those procedures to system operations.

Chapter 7 examines antecedents related to regulators. It discusses the importance of regulators in both creating the rules under which complex systems operate, and enforcing those rules to insure safe operation. Instances of lax regulation in which the regulator created antecedents to organizational errors in a variety of settings, including the financial sector, are discussed.

Chapter 8 assesses the impact of culture on error. Two types of culture, national and company related, are examined. Although they are distinct in terms of their relationship to antecedents, they share characteristics that influence operator performance. Several accidents, which illustrate the types of antecedents that can arise from cultural factors, are reviewed.

Chapter 9 reviews operator teams and error antecedents that are unique to teams. The complexities of contemporary systems often call for operator teams with diverse skills to operate the systems. System features that necessitate the use of operator teams, the errors that members of these teams could commit, and their antecedents, are examined.

Chapter 10 addresses the first of the data sources investigators rely on, electronic data that system recorders capture and record. Types of recorders used in different systems are examined and their contribution to the investigation of error in those systems discussed. A recent accident is presented to illustrate how recorded data can provide a comprehensive view of the system state and an understanding of the errors leading to an accident.

Chapter 11 discusses written documentation, an additional data source for investigators. Documentation critical to investigations including records that companies and government agencies maintain, such as medical and personnel records, and factors that affect the quality of that information, are discussed. Several accidents are reviewed to illustrate how written documentation can help investigators understand both the errors that may have led to events in complex systems and their antecedents.

Chapter 12 focuses on a third type of data for investigators, interview data, and their use in error investigations. Memory and memory errors are reviewed, and their effects on interviewee recall discussed. Types of interviewees are discussed and the factors pertaining to each, such as the type of information expected, the interview location, and the time since the event, examined. Suggestions to enhance interview quality and maximize the information they can provide are offered.

Chapter 13 begins Section IV of the book, contemporary issues in error in complex systems. This chapter examines antecedents that are exclusive to the maintenance and inspection environment. With the exceptions of Reason and Hobbs (2003) and Drury (1998), researchers have generally paid little attention to understanding maintenance and inspection errors. Antecedents to these errors include environmental factors, tool design, the tasks themselves, and other factors related to the distinctive demands of system maintenance and inspection.

Chapter 14 reviews situation awareness and decision making, and their relationship to system safety. Factors that can influence situation awareness are discussed, many of which are also reviewed as error antecedents elsewhere in the book. The relationship of situation awareness to decision making is outlined. Two models of decision making are reviewed, classical decision making, applied to relatively static domains and naturalistic decision making, employed in dynamic environments. A case study involving a critical decision-making error is presented to illustrate the role of decision making in system safety.

Chapter 15 examines a third issue in error, automation, a subject that has received considerable attention in the literature on error and complex systems, and in accident investigations. Automated systems have introduced unique antecedents. Their effects on operator performance in an accident involving a marine vessel are examined.

Chapter 16 begins the section that reviews issues previously discussed in the book. It focuses on an accident in detail to illustrate many of the concepts and methodology presented throughout the book. An automation-related accident involving a Boeing 777, in which a series of interacting antecedents led to a basic and rather simple operator error, is detailed. The roles of the manufacturer, the company, and the regulator are examined in detail.

In the final Chapter 17, goals outlined in the first chapter are reexamined. Major principles of human error investigation, as discussed in earlier chapters are reviewed, and ways that investigations into error can be used proactively to enhance system safety, suggested.

Each chapter is meant to stand alone, so that those interested in a specific issue or technique can readily refer to the section of interest. The chapters may also be read out of sequence if desired. Nonetheless, reading them sequentially will provide a logical overview of the literature and the field itself. It is hoped that by the end of the book the reader will feel confident to effectively investigate error in a complex system.

References

Drury, C. G. 1998. Human factors in aviation maintenance. In D. J. Garland, J. A. Wise, and V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 591–606). Mahwah, NJ: Erlbaum.

Langewiesche, W. 1998. The lessons of ValuJet 592. *The Atlantic Monthly*, March, 81–98.
Moray, N. 2000. Culture, politics and ergonomics. *Ergonomics*, 43, 858–868.
National Transportation Safety Board. 1997. Aircraft accident report. In-Flight Fire and Impact with Terrain, ValuJet Airlines, Flight 592, DC-9-32, N904VJ, Everglades, Near Miami, Florida, May 11, 1996. Report Number: AAR-97-06. Washington, DC.
Perrow, C. 1999. *Normal accidents: Living with high-risk technologies* (2nd ed.). Princeton, NJ: Princeton University Press.
Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.
Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.
Reason, J. and Hobbs, A. 2003. *Managing maintenance error*. Aldershot, England: Ashgate.
Woods, D. D., Johannesen, L. J., Cook, R. I., and Sarter, N. B. 1994. *Behind human error: Cognitive systems, computers, and hindsight*. Wright-Patterson Air Force Base, OH: Crew Systems Ergonomics Information Analysis Center (CSERIAC).

Section I

Errors and Complex Systems

2

Errors, Complex Systems, Accidents, and Investigations

> Patient accident reconstruction reveals the banality and triviality behind most catastrophes.
>
> **Perrow, 1999, p. 9**
> *Normal Accidents*

Operators and Complex Systems

There have been extraordinary changes in the machines that affect our daily lives. The equipment has become more complex, more sophisticated and more automated, while becoming more central to our activities. In commercial aviation, for example, two pilots were needed to fly the first commercially successful air transport aircraft, the Douglas DC-3, an aircraft that was designed over 80 years ago. The DC-3 could carry about 20 passengers at a speed of about 200 miles an hour over several hundred miles. Today, two pilots are also needed to operate a passenger-carrying aircraft, the Airbus A-380, but this aircraft transports over 500 passengers, several thousand miles, at speeds in excess of 500 miles an hour. Although the acquisition and operating costs of the A-380 are many times those of its predecessor, the per-seat operating costs are lower. This has helped to make air transportation affordable to many more people than in the DC-3 era.

Yet, there is a price that is paid for these technological advances. While the cost of travel has gone down substantially since the DC-3 era because modern aircraft transport more people at lower cost than previously, more people are also exposed to the consequences of operator errors than was true of the earlier era. Accidents that occurred a century ago, such as ship fires, exposed relatively fewer people to risk whereas today thousands have been lost in

single events, such as the 1987 sinking of a ferry in the Philippines, or in the 1984 chemical accident in Bhopal, India.*

Complex Systems

People work with machines routinely and when they do they are machine operators. Whether operating lawn mowers, automobiles, tablets, or power saws, people use machines to perform tasks that they either cannot do themselves, or can perform more quickly, accurately, or economically with the machines. Together the operator and the machine form a system in which each is a critical and essential system component. As Chapanis (1996) defines,

> A system is an interacting combination, at any level of complexity, of people, materials, tools, machines, software, facilities, and procedures designed to work together for some common purpose. (p. 22)

Complex systems, which employ machines that require multiple operators with extensive training, support our way of life. They provide clean water and sewage treatment, electrical power, and facilitate global finance, to name but a few. These systems, considerably more sophisticated than, say a person operating a lawn mower, have become so integral to our daily activities that in the event they fail whole economies can be threatened.

However, as Perrow (1999) notes, the complexity of such systems has increased inordinately.

> We have produced designs so complicated that we cannot anticipate all the possible interactions of the inevitable failures; we add safety devices that are deceived or avoided or defeated by hidden paths in the systems. The systems have become more complicated because either they are dealing with more deadly substances, or we demand they function in ever more hostile environments or with ever greater speed and volume. (p. 12)

As our dependence on systems increases, more is asked of them, and with their increasing technical capabilities we have witnessed increased complexity. Complex systems are more than merely operators and equipment working together, they are entities that typically perform numerous tasks of considerable import to both companies and individuals.

Although complex systems need not necessarily be high-risk systems, that is, systems in which the consequences of failure can be catastrophic, many authors apply the terms interchangeably. Systems that are sufficiently complex are often high-risk systems, if for no other reason than because so many people depend on them and thus interruptions from service can dramatically

* On December 29, 1987, the ferry *Dona Paz* sank off the coast of Manila killing 4235 people. On December 3, 1984, a gas leak at Union Carbide's chemical processing plant in Bhopal, India, killed an estimated 3800 people and injured thousands more.

affect our lives. Nonetheless, while the focus of this book is on complex systems, the methodology to investigate human error described can be readily applied to simple systems as well—even to the system in which one person operates a lawn mower.

Operators

Operators interact with and control complex systems, and consequently play a central role in system safety. Despite the diversity of skills they need, equipment used, and settings in which they operate, one term can be used to describe them. While some have used terms such as "actor," "technician," "pilot," "controller," and "worker," the term operator will be used presently. In reference to maintenance activities, the terms technician and inspector will be used, as appropriate.

Whether it is a financial, air transport, or electrical generating system, operators essentially perform two functions: they monitor the system and they control its operations. To do so, they obtain information from the system and its operating environment, using their knowledge and experience, with the information, to understand the system state. Based on their understanding of the system, they modify operations, as needed, according to operational phase and the system-related information they perceive.

Because of the potential severity of the consequences of error in complex systems, operators are expected to be skilled and qualified. They are the first line of defense in trying to limit the effects of system anomalies from becoming catastrophic. However, operators sometimes precipitate rather than prevent system incidents or accidents.

Normal Accidents and Complex Systems

The changes that have taken place over time in the complexity of these systems have fundamentally altered the relationship between operators and the machines they control. Once directly controlling the machines, operators now largely supervise their operations. These tasks are typically performed at a higher cognitive and a lower physical level than was true of operators of earlier times who largely controlled the machines manually.

Charles Perrow (1999) suggests that complex systems have changed to the extent that "interactive complexity" and "tight coupling" have made "normal accidents" inevitable. That is, as systems have become more efficient, powerful, and diverse in the tasks they perform, the consequences of system failures have grown. In response, designers have increased the number of defenses against system malfunctions and operator errors, thus increasing internal system complexity. At the same time, systems have become tightly coupled, so that processes occur in strict, time-dependent sequences, with little tolerance for variability. Should a component or subsystem experience even a minor failure, little or no "slack" would be available within

the system, and the entire process could be impacted. The combination of increased complexity and tight coupling has created system states that neither designers nor operators had anticipated.

Perrow suggests that unanticipated events in tightly coupled and highly complex systems will inevitably lead to accidents. As he explains,

> If interactive complexity and tight coupling—system characteristics—inevitably will produce an accident, I believe we are justified in calling it a normal accident, or a system accident. The odd term normal accident is meant to signal that, given the system characteristics, multiple and unexpected interactions of failures are inevitable. (p. 5)

It seems difficult to accept that fundamental characteristics of complex systems have made catastrophic accidents "normal." Perrow, however, has greatly influenced how incidents and accidents in complex systems are considered by focusing not on the operator as the cause of an accident or incident but on the system itself and its design.

James Reason (1990, 1997), the British human factors researcher, expanded on Perrow's theory by focusing on the manner in which system operation as well as system design can lead to errors. He suggests that two kinds of accidents occur in complex systems: one results from the actions of people, which he terms "individual accidents," and the other "organizational accidents," which results largely from the actions of companies and their managers. Reason's (1997) description of organizational accidents has much in common with Perrow's normal accidents,

> These [organizational accidents] are the comparatively rare, but often catastrophic, events that occur within complex modern technologies such as nuclear power plants, commercial aviation, the petrochemical industry, chemical process plants, marine and rail transport, banks and stadiums. Organizational accidents have multiple causes involving many people operating at different levels of their respective companies. Organizational accidents…can have devastating effects on uninvolved populations, assets and the environment. (p. 1)

Both Reason and Perrow suggest that, given changes in the nature and function of these systems, new and largely unanticipated opportunities for human error have been created.

Vicente (1999) elaborates on the work of Reason and Perrow and identifies elements of what he refers to as "sociotechnical systems," which have increased the demands on system operators. These include the social needs and different perspectives of team members that often operate complex systems, the increasing distance among operators and between operators and equipment, the dynamic nature of systems, increasing system automation, and uncertain data. By escalating the demands on operators, each element has increased the pressure on them to perform without error.

Human fallibilities being what they are, there will always be a possibility that an operator will commit an error, and that the consequences of even "minor" errors will present a threat to the safety of complex systems. Some, such as Senders and Moray (1991), Hollnagel (1993), and Reason (1997), suggest that the impossibility of eliminating operator error should be recognized, by focusing not on error but instead on minimizing the consequences of errors.

Human Error

Most errors are insignificant and quickly forgotten. The relatively minor consequences of most human errors justify the relative inattention we pay them. Some circumstances even call for errors, such as when learning new skills. Children who learn to ride bicycles are expected to make numerous errors initially, but fewer errors as they become more proficient, until they reach the point of riding without error. Designers and training professionals, recognizing the value of errors in learning environments, have developed system simulators that enable operators to be trained in operating systems in realistic environments, free of the consequences of error.

People require feedback after they have erred; without it, they may not even realize that they have committed errors. Someone who forgets to deposit money into a checking account may continue to write checks without recognizing that the account lacks sufficient funds. That person would not likely be considered to be committing an error each time he or she wrote a check. Rather, most would consider the person to have committed only one error—the initial failure to deposit funds into the account.

It should be apparent that the nature of errors and the interpretation and determination of their significance are largely contextual. Turning a crank the wrong way to close an automobile window is a minor error that would probably be quickly forgotten. On the other hand, turning a knob in the control room of a nuclear power plant in the wrong direction can lead to a nuclear accident. Both errors are similar—relatively simple acts of rotating a control in the wrong direction—yet under certain conditions an otherwise minor error can cause catastrophic consequences. What ultimately differentiates errors are their contexts and the relative severity of their consequences.

Theories of Error

Modern error theory suggests that in complex systems, operator errors are the logical consequences of antecedents or precursors that had been present

in the systems. Theorists have not always considered system antecedents to play as large a role in error causation as is considered today.

Freud

Freud and his students believe that error is a product of the unconscious drives of the person (e.g., Brenner, 1964). Those who erred are considered less effective and possibly more deficient than those who do not, an interpretation that has had wide influence on theories of error and on subsequent research. For example, the concept of "accident proneness," influenced by Freud's view of error, attributed to certain people a greater likelihood of committing errors than to others because of their personal traits. However, studies (e.g., Rodgers and Blanchard, 1993; Lawton and Parker, 1998) have found serious methodological deficiencies in the initial studies upon which much of the later assumptions about error proneness had been based. For example, the failure to control the rates of exposure to risk minimized the applicability of conclusions derived. Lawton and Parker conclude, "…it proved impossible to produce an overall stable profile of the accident-prone individual or to determine whether someone had an accident-prone personality" (p. 656). The application of Freud's theories (he used multiple theories to explain human behavior) outside of clinical settings has largely fallen into disfavor as both behavioral and cognitive psychological theories have gained increasing acceptance. Unlike Freud, error theorists since his day consider the setting in which errors are committed when examining error to be far more important than the characteristics of the person committing the error.

Heinrich

Heinrich (1931, 1941) was among the first to systematically study accident causation in industrial settings. He suggested that incidents and accidents can be prevented by breaking the causal link in the sequence or chain of events that led up to them. Focusing on occupational injuries, that is job-related injuries, he suggested that accidents result from a sequence of events involving people's interactions with machines. One step leads to others in a fixed and logical order, much as a falling domino causes subsequent standing dominoes to fall, ultimately leading to an incident or accident. Heinrich suggested that incidents and accidents form a triangle or pyramid of frequency, with non-injury incidents, which occur the least often, located at the bottom of the pyramid, incidents with minor injuries, which occur more often than non-injury incidents, at the middle of the pyramid, and accidents with serious injuries, which occur the least often, at the top of the pyramid.

To Heinrich, two critical underlying factors leading to accidents were personal or mechanical hazards resulting from carelessness and poorly designed or improperly maintained equipment. Carelessness and other "faults" were, to Heinrich, the result of environmental influences, that is, the environment

in which people were raised, or traits that they inherited. Heinrich's work, with its systematic study of accident causation, had considerable influence on our view of accident causation. Coury, Ellingstad, and Kolly (2010) wrote that as a result of Heinrich's work, many have come to view accident causation as a series of links in a chain, to be prevented by breaking the link or sequence of events.

Norman

Norman (1981, 1988) studied both cognitive and motor errors and differentiated between two types of errors: slips and mistakes. Slips are action errors or errors of execution that are triggered by schemas, a person's organized knowledge, memories, and experiences. Slips can result from errors in the formation of intents to act, faulty triggering of schemas, or mental images of phenomena, among other factors. He categorized six types of slips, exemplified by such relatively minor errors as striking the wrong key on a computer keyboard, pouring coffee into the cereal bowl instead of the cup adjacent to the bowl, and speaking a word other than the one intended.

Mistakes are errors of thought in which a person's cognitive activities lead to actions or decisions that are contrary to what was intended. To Norman, slips are errors that logically result from the combination of environmental triggers and schemas. Applying the lessons of slips to design, such as standardizing the direction of rotation of window cranks in automobiles, would, to Norman, reduce the number of environmental triggers and therefore reduce the likelihood of slips.

Rasmussen

Jens Rasmussen (1983), a Danish researcher, expanded the cognitive aspects of error that Norman and others described, by defining three levels of operator performance and three types of associated errors: skill-, knowledge-, and rule-based. Skill-based performance, the simplest of the three, relies on skills that a person acquires overtime and stores in memory. Skill-based performance errors are similar to Norman's slips in that they are largely errors of execution. With rule-based performance, more advanced than skill-based, operators apply rules to situations that are similar to those that they have encountered through experience and training. Rule-based performance errors result from the inability to recognize or understand the situations or circumstances encountered. This can occur when the information necessary to understand the situation is unavailable, or the operator applies the wrong rule to unfamiliar circumstances.

Rasmussen maintains that the highest level of performance is knowledge-based. Rather than applying simple motor tasks or rules to situations that are similar to those previously encountered, the operator applies previously learned information, or information obtained through previous experience,

to novel situations to analyze or solve problems associated with those situations. Knowledge-based performance errors result primarily from shortcomings in operator knowledge or limitations in his or her ability to apply existing knowledge to new situations.

Reason

James Reason (1990) enlarged the focus of earlier definitions of errors and further distinguished among basic error types. He defines slips as others have—relatively minor errors of execution, but he also identifies an additional type of error, a lapse, which he characterizes as primarily a memory error. A lapse is less observable than a slip and occurs when a person becomes distracted when about to perform a task, or omits a step when attempting to complete the task.

Reason also distinguishes between mistakes and violations. Both are errors of intent—mistakes result from inappropriate intentions or incorrect diagnoses of situations, violations are actions that are deliberately nonstandard or contrary to procedures.

Reason does not necessarily consider violations to be negative. Operators often develop violations to accomplish tasks in ways they believe would be more efficient than those accomplished by following procedures that designers and managers developed. By contrast, Reason considers a deliberate act, intended to undermine the safety of the system, to be sabotage.

Reason's categorization of errors corresponds to Rasmussen's performance-based errors. Slips and lapses are action errors that involve skill-based performance while mistakes involve either rule- or knowledge-based performance.

Reason, however, added to previous error theories by addressing the role of designers and company managers in operator errors, that is, those who function at the higher levels of system operations, at what he labels the "blunt end" of a system. Those at the blunt end commit what he terms "latent errors" (but later (1997) referred to as "latent conditions") within a system. Operators, located at the "sharp end" of a system, commit what he calls "active errors," errors that directly lead to accidents.

Operators' active errors are influenced, Reason argues, by latent errors that those at the blunt end have committed, errors that lie hidden within the system. Although active errors lead to consequences that are almost immediately recognized, the consequences of latent errors may go unnoticed for some time, becoming manifest only when a combination of factors weaken system defenses against active errors. Designers and managers place internal defenses in systems to prevent errors from leading to incidents and accidents in recognition of the potential fallibility of human performance. However, should the defenses fail when an operator commits an error, catastrophic consequences could occur.

Reason (1990) uses a medical analogy to explain how latent errors can affect complex systems,

> There appear to be similarities between latent failures in complex technological systems and resident pathogens in the human body. The resident pathogen metaphor emphasises the significance of causal factors present in the system before an accident sequence actually begins. All man-made systems contain potentially destructive agencies, like the pathogens within the human body. At any one time, each complex system will have within it a certain number of latent failures, whose effects are not immediately apparent but that can serve both to promote unsafe acts and to weaken its defence mechanisms. For the most part, these are tolerated, detected and corrected…but every now and again a set of external circumstances—called here local triggers—arise that combines with these resident pathogens in subtle and often unlikely ways to thwart the system's defences and to bring about its catastrophic breakdown. (p. 197)

Reason illustrates how company-related defenses and resident pathogens affect safety by pointing to slices of Swiss cheese that are lined up against each other (Figure 2.1). Unforeseen system deficiencies, such as questionable managerial and design decisions, precede managers' actions. These lead to "psychological precursors" among operators such as reactions to stress or to other aspects of the "human condition," and to unsafe acts. These represent the holes in the Swiss cheese whereas the solid parts of the cheese slices represent company defenses against the hazards of unsafe acts. If the Swiss cheese slices were placed one against the other, the holes or deficiencies would be unlikely to line up in sequence. Company-related defenses,

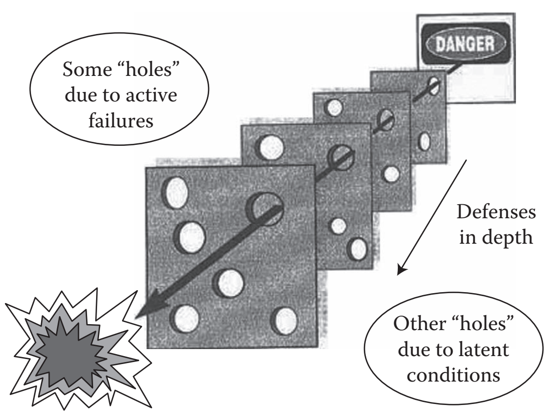

FIGURE 2.1
Reason's model of error. (From Reason, J. T. 1997. Aldershot, England: Ashgate. Copyright Ashgate Publishing. Reprinted with permission.)

the solid portions of the cheese, would block an error from penetrating. However, should the deficiencies (holes) line up uniquely, an active error could breach the system, much as an object could move through the holes in the slices, an unsafe act would not be prevented from affecting the system, and an accident could result.

To Reason, even though managerial and design errors are unlikely to lead directly to accidents and incidents, an examination of human error should assess the actions and decisions of managers and designers at the blunt end at least as much, if not more, than the actions of the system operators at the sharp end. His description of the role of both design and company-related or managerial antecedents of error has greatly influenced our understanding of error, largely because of its simplicity, rationality, and ease of understanding. Further, his approach to developing a model to explain error causation was also influential. For example, the International Civil Aviation Organization (ICAO) has formally adopted Reason's model of error for its member states to facilitate their understanding of human factors issues and aviation safety (ICAO, 1993).

Dekker and Pruchnicki (2014) updated Reason's model, in the light of several major accidents and theoretical work that had been conducted since his initial work on error was published. Errors in complex systems that lead to accidents and incidents, they argue, are often preceded by extensive periods, which they refer to as "incubation periods," in which the latent errors of which Reason speaks, or organizational shortcomings, gradually increase but remain unrecognized. These shortcomings maybe taken for granted, or are unrecognized over time as the risks increase and the organization or company gradually "drifts" toward an accident. As they note:

> Pressures of scarcity and competition, the intransparency and size of complex systems, the patterns of information that surround decision makers, and the incremental nature of their decisions over time, all enter into the incubation period of future accidents. Incubation happens through normal processes of reconciling differential pressures on an organisation (efficiency, capacity utilisation, safety) against a background of uncertain technology and imperfect knowledge. Incubation is about incremental, or small, seemingly insignificant steps eventually contributing to extraordinary unforeseen events. (p. 541)

What Is Error

Researchers generally agree on the meaning of an error. To Senders and Moray (1991), it is "something [that] has been done which was not intended by the actor, not desired by a set of rules or an external observer, or that led the task or system outside its acceptable limits" (p. 25). Reason (1990) sees an error as "a generic term to encompass all those occasions in which a

planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" (p. 5). Woods, Johannesen, Cook, and Sarter (1994) define error as "a specific variety of human performance that is so clearly and significantly substandard and flawed when viewed in retrospect that there is no doubt that it should have been viewed by the practitioner as substandard *at the time the act was committed or omitted*" (emphasis in original, p. 2).

Hollnagel (1993) believes that the term "human error" is too simplistic and that "erroneous action" should be used in its place. An erroneous action, he explains, "is an action which fails to produce the expected result and which therefore leads to an unwanted consequence" (p. 67). He argues that one should not make judgments regarding the cause of the event. The term erroneous action, unlike error, implies no judgment and accounts for the context in which the action occurs.

Despite some disagreement in defining error, most researchers agree on the fundamental aspects of error, seeing it as the result of something that people do or intend to do that leads to outcomes different from what they had expected. Therefore, to be consistent with these views, error will be defined in this book as *an action or decision that results in one or more unintended negative outcomes*. Errors that occur in learning or training environments, where they are expected, tolerated, and used to enhance and enlarge a person's repertoire of skills and knowledge, will not be considered further.

For our purposes even though researchers have described multiple types of errors, insofar as accident or incident investigations are concerned, only two types of errors are important, action errors and decision errors. In an action error, an operator does something wrong, such as shuts a system down that should have continued in operation, or does something contrary to what had been called for by company procedures. Decision errors refer to incorrect decisions that operators make, such as misinterpreting weather information and proceeding into an area of adverse weather. In general, errors related to equipment control design antecedents tend to be action errors. Errors that call for interpretation, such as navigation or understanding the meaning of multiple alarms, tend to be decision errors.

Error Taxonomies

Senders and Moray (1991) developed an error taxonomy based largely on the work of Rasmussen, Reason, and others, to better understand errors and the circumstances in which people commit errors. Their taxonomy suggests that error results from one or more of the following factors, operating alone or together, the person's "information-processing system" or cognitive processes; environmental effects; pressures on and biases of the individual; and the individual's mental, emotional, and attentional states. This taxonomy describes errors in terms of four levels; "phenomenological" or observable

manifestations of error, cognitive processes, goal-directed behaviors, and external factors, such as environmental distractions or equipment design factors.

Shappell and Wiegmann (1997, 2001) propose a taxonomy to apply to the investigation of human error in aircraft accidents, a model that has since been embraced and applied by such U.S. agencies as the U.S. Coast Guard, in the investigation of marine accidents. Expanding on Reason's work, their taxonomy differentiates among operations that are influenced by unsafe supervision, unsafe conditions, and unsafe acts. Unsafe acts include various error categories, while unsafe conditions include both behavioral and physiological states and conditions. Unsafe supervision, which distinguishes between unsafe supervisory actions that are unforeseen and those that are foreseen, incorporates elements that Reason would likely term latent errors or latent conditions.

Sutcliffe and Rugg (1998) propose a taxonomy based on Hollnagel's (1993), that distinguishes between error phenotypes (the manifestation of errors) and genotypes (their underlying causes). They group the operational descriptions of errors into six categories and divide causal factors into three groups: cognitive, social and company-related, and equipment or tool design.

O'Hare (2000) proposed a taxonomy, referred to as the "Wheel of Misfortune," to serve as a link between researchers in human error and accident investigators seeking to apply research findings to incidents or accidents. As with Reason, he delineates company-related defenses that could allow operator error to affect system operations unchecked.

Incidents, Accidents, and Investigations

Incidents and Accidents

Loimer and Guarnieri (1996), in a review of accident history, described how the meaning of term has changed over the years. Aristotle, for example, used accidents to refer to nonessential or extrinsic characteristics of people and things. Thus, someone could have accidental qualities, for example, one leg, and still retain human characteristics. About the fourteenth century, the English began to use a more modern understanding of the term, closer to that of contemporary times, that is, "to happen by chance; a misfortune; an event that happens without foresight or expectation" (p. 102), a usage initially found in Chaucer in 1374. As the industrial revolution developed in the late eighteenth century, injuries of workers in the textile, railroad, and mining industries began to emerge. These were new types of accidents that occurred among workers who were operating what were then complex systems, but of course system operations required considerably more muscular effort than

is true today, with little design and training consideration directed to worker safety. Loimer and Guarnieri noted that accident attribution began to change around that time as well, from being considered the result of divine influence that had been common in the middle ages to that of worker causation, for example, carelessness, of the industrial revolution.

Coury et al. (2010) wrote that World War II brought about considerable complexity in systems such as aircraft used in the war effort. System complexity was also influenced by the rapid development of and the need to quickly utilize these systems, which called for hastily training people to operate them, factors that contributed to high rates of training accidents. In attempting to understand the reasons for the accident rates, researchers focused on operator error from the perspective of factors related to the design of the system controls and displays, rather than on the operator himself or herself, a focus that led to research to better understand how machine design can lead to error.

Process Accidents

Today, researchers devote considerable attention to examining on the job injuries, especially in such industries as petrochemical processing and mining (e.g., Flin, Mearns, O'Connor, and Bryden, 2000). But the nature of accident causation is typically different in worker injury accidents than it is in process accidents. In the former, accident causation is largely considered the result of flaws in control design, training, or worker attention. In the latter, the type that is the focus of this book, causation is generally attributed to flaws in the system itself, which can include design, training, and worker attention but typically involves elements of the entire system. Certainly, the consequences of the two are different as well. Occupational accident consequences primarily affect system operators while process accidents may affect the workers or operators, but as often affect those uninvolved in system operations, such as passengers in transportation accidents, or residents near a nuclear generating station that sustained a radiation leak.

Senders and Moray (1991), focusing on process accidents, term an accident "a manifestation of the consequence of an expression of an error" (p. 104). Others suggest that accidents are events that are accompanied by injury to persons or damage to property. In this way, even minor injuries can change the categorization of an incident, typically involving an occurrence of more minor consequences, to that of an accident, an occurrence with often major or severe consequences. Those consequences can be injuries to persons, damage to property, and or pollution of the air, water, or land environment.

Perrow (1999) distinguished between accidents and incidents largely by the extent of the damage to property and injuries to persons. He considers incidents to be events that damage parts of the system, and accidents events that damage subsystems or the system as a whole, resulting in the

immediate shutdown of the system. Although a system accident may start with a component failure, it is primarily distinguished by the occurrence of multiple failures interacting in unanticipated ways. Catastrophic system accidents may bring injury or death to bystanders uninvolved with the system, or even to those not yet born. For example, accidents in nuclear generating stations can lead to birth defects and fertility difficulties among those exposed to radiation released in the accident.

Legal Definitions

Whether an event is classified as an incident or an accident can have considerable influence on data analysis, research, as well as on civil or criminal proceedings. Therefore, much attention has been devoted to the classification of accidents. Loimer and Guarnieri (1996) describe the historic tradition, dating to the middle ages, of accident causation being attributed to acts of god as compared to acts of people. Today, they note, any accident that is caused, directly or indirectly, by natural causes "without human intervention" is considered to be "an act of god." In this respect, the March 11, 2011, accident at the Fukushima Daiichi nuclear power plant, which occurred in the aftermath of a magnitude 9 earthquake and subsequent tsunami, may be considered an act of god, despite the fact that the direct cause of the nuclear accident was the flooding of the diesel generators that provided electric power for emergency water cooling to the nuclear core. Water from the tsunami entered and contaminated the generators, which had been placed at ground level, thereby making them susceptible to flooding given the reactor's proximity to the sea. For our purposes, even though the flooding was a naturally caused event, the placement of the generators adjacent to the sea was not, and thus investigators would still want to examine the system shortcomings that allowed the tsunami to result in a nuclear accident.

In general, the contemporary classification of events into accidents ignores the natural- versus person-caused aspect to focus on the severity of the consequences. Consequently, specific definitions in both international law and in the laws of individual nations define accidents. For example, ICAO (1970) defines an aircraft accident as,

> An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:
> a person is fatally injured…or
> the aircraft sustains damage or structural failure…or
> the aircraft is missing or is completely inaccessible. (p. 1)

ICAO also precisely defines injury and death associated with an accident. Injuries include broken bones other than fingers, toes, or noses, or any of the following: hospitalization for at least 48 hours within 7 days of the event, severe lacerations, internal organ damage, second- or third-degree burns

over 5% or more of the body, or exposure to infectious substances or injurious radiation. A fatal injury is defined as a death from accident-related injuries that occurred within 30 days of the accident. An incident is an event that is less serious than an accident.

Other government or international agencies use similar definitions, albeit specific to the particular domain. For example, the U.S. Coast Guard defines a marine accident as,

> Any casualty or accident involving any vessel other than public vessels if such casualty or accident occurs upon the navigable waters of the United States, its territories or possessions or any casualty or accident wherever such casualty or accident may occur involving any United States vessel which is not a public vessel…[including] any accidental grounding, or any occurrence involving a vessel which results in damage by or to the vessel, its apparel, gear, or cargo, or injury or loss of life of any person; and includes among other things, collisions, strandings, groundings, founderings, heavy weather damage, fires, explosions, failure of gear and equipment and any other damage which might affect or impair the seaworthiness of the vessel…[and] occurrences of loss of life or injury to any person while diving from a vessel and using underwater breathing apparatus. (46 Code of Federal Regulations 4.03-1 (a) and (b))

Under U.S. law, 46 U.S. Code § 6101, a major marine accident, referred to as a "major marine casualty," is defined as:

> …a casualty involving a vessel, other than a public vessel, that results in—
>
> 1. The loss of 6 or more lives.
> 2. The loss of a mechanically propelled vessel of 100 or more gross tons.
> 3. Property damage initially estimated at $500,000 or more.
> 4. Or serious threat, as determined by the Commandant of the Coast Guard with concurrence by the Chairman of the National Transportation Safety Board, to life, property, or the environment by hazardous materials.

To avoid confusion among the various definitions, both incidents and accidents in complex systems will be defined as: *unexpected events that cause substantial property or environmental damage and/or serious injuries to people.* Accidents lead to consequences that are more severe than those of incidents.

Investigations

Coury et al. (2010) reviewed the history of accident investigations in complex systems, focusing on transportation accident investigations, and noted how the evolution of accident investigation matched the corresponding evolution

in technology. As technology became more reliable, investigations focused less on hardware and more on the role of those who operate the systems. Although companies often investigated the accidents of systems they owned and operated, governments also played a role in the investigations, often initially in the role of coroners' inquests. Eventually, investigations went beyond identifying the accident cause as operator error, or pilot error in the case of aviation, to focus on the nature of the interaction between the operator and the system being operated. Coury et al. (2010) note that with the advent of World War II, human factors emerged as a major element of accident invstigations. "No longer was it acceptable," they note, "to merely identify the type of pilot error; now the design of the system and its contribution to the error must also be considered" (p. 16). Further, as investigators gained a more sophisticated understanding of error in accident causation, in aviation accident investigations,

> Pilot and operator error were no longer simply categories within causal taxonomies but instead reflected a more complex interaction between people and machines that could be empirically studied and even "designed out" of human machine systems. As a result, human factors and human performance assumed a larger role in accident investigation, in which safety issues were related to potential incompatibilities with human information processing, and cognition and influenced the way accident investigators thought about pilot actions. (p. 16)

Le Coze (2013), in a review of major models of investigations, describes two "waves" of highly visible major accidents that occurred in the past 20–30 years that have impacted our view of accidents. The recent accidents, which involved a variety of complex systems,

> …all come under the same intense national and often also international interest and scrutiny by the media, justice systems, civil society, states, financial markets, industry and professions. They have a strong symbolic component, where each time, and probably at Fukushima more than elsewhere, a belief about the safety of these systems that had previously been taken for granted has seriously been undermined. (p. 201)

The accidents to which he referred include, in the first wave, the 1986 explosion of the space shuttle *Challenger*, the ground collision at Tenerife of two Boeing 747s, and the grounding of the tanker *Exxon Valdez*. The accidents in the second wave include the grounding of the cruise vessel *Costa Concordia*, and the meltdown at the Fukushima Daiichi nuclear power plant that followed the earthquake and tsunami.

Although today accident investigations are conducted to identify the cause or causes of accidents and thereby develop ways of mitigating future opportunities for error and malfunctions, investigations may fulfill multiple missions as well. Senders and Moray (1991) acknowledge that investigations can

be conducted for a variety of purposes. "What is deemed to be the cause of an accident or error," they write, "depends on the purpose of the inquiry. *There is no absolute cause*" (emphasis in original, p. 106). For example, law enforcement personnel conduct criminal investigations to identify perpetrators of crimes and to collect sufficient evidence to prosecute and convict them. Governments investigate accidents to protect the public by ensuring that the necessary steps are taken to prevent similar occurrences, mandating necessary changes to the system or changing the nature of its oversight of the system. Kahan (1999) notes that governments have become increasingly involved in investigating transportation accidents. Whereas governments initially investigated accidents on an individual basis and assigned investigators to the investigations as they occurred, many governments have established agencies with full-time investigative staffs for the exclusive purpose of investigating accidents.

Rasmussen, Pejtersen, and Goodstein (1994) contend that investigators examine system events according to a variety of viewpoints. These include a common sense one, and those of the scientist, reliability analyst, therapist, attorney, and designer, respectively. Each influences what Rasmussen et al. (1994) refer to as an investigation's "stopping point," that is, the point at which the investigator believes that the objectives of the investigation have been met.

For example, an investigator with a common sense perspective stops the investigation when satisfied that the explanation of the event is reasonable and familiar. The scientist concludes the investigation when the mechanisms linking the error antecedent to the operator who committed the error are known, and the attorney concludes the investigation when the one responsible for the event, usually someone directly involved in the operation who can be punished for his or her actions or decisions, is identified. The objective advocated in this book is based on the suggestions of Rasmussen et al. (1994). Investigators should conduct investigations to learn what caused an incident or accident by establishing a link between antecedent and error, so that changes can be implemented to prevent future occurrences.

Dekker (2015) identified four purposes of accident investigations, epistemological, that is, establishing what happened; preventive, identifying pathways to avoidance; moral, tracing the transgressions that were committed and reinforcing moral and regulatory boundaries; and existential, finding an explanation for the suffering that occurred. These purposes affect the conduct of accident investigations. For example, the existential and moral needs Dekker identified, and the public policy implications Le Coze (2013) described, are addressed by the direct role of governments in investigations. Relying on government rather than industry to conduct such investigations, for example, satisfies the public need for answers to what happened, and the need for reassurance that action will be taken to address the shortcomings that led to the accident. Stoop and Dekker (2012), focusing on aviation accident investigations, also note the evolution of investigations as technology has advanced, to where today we accept failure as "normal," where resilient

systems can allocate scarce safety resources as needed in response to different system states.

Today, it can be said that investigations, particularly those of major accidents, serve multiple functions. These serve not just to determine how the accident developed and was caused, so that changes in the system can be implemented to prevent similar accidents in the future, but for needs that transcend those of the accident itself. As Le Coze (2008) writes,

> Accident investigations are not research works with the aim of theorising. They are investigative projects, set up in a specific political context following a disaster, for understanding its circumstances and for making recommendations. They also serve a societal need for transparency. These are big projects carried out through a short period of time, often within months. The number of staff is important. This staff includes people collecting the data, advisors and consultants from university and industry for various aspects ranging from technical to organisational and human factors issues, administrative people, etc. (p. 140)

Accident investigations, where investigators identify the factors that led to an accident, analyze how those factors played a role in the circumstances in which the accident occurred, and ultimately suggest ways to prevent their recurrence, call for data collection and analysis skills. Unlike empirical research, which is overseen through peer review, theory testing, and/or experimental replication, major accident investigations are typically subject to governmental or corporate review. In addition, investigations face time pressures that can be considerable. Unless the investigations can be conducted quickly, the findings of the investigation could have little significance in terms of risk mitigation and public need.

Further, analytical rules of accident investigations tend to be legalistic, using logical consistency and the preponderance of evidence. Based on the facts gathered, investigators develop a logical explanation of the events that led to an accident. This generally results in identifying errors on the part of individual operators or operator teams (including maintenance personnel), failures of some mechanical component or system, a failure that may have been the result of an operator error, and/or errors in actions, inactions and/or shortcomings in decisions of organizational managers. Although some investigative agencies shy away from identifying operator errors, the practice is still commonplace among such investigative agencies as the United States National Transportation Safety Board, the British Air Accidents Investigation Branch and the Marine Accidents Investigation Branch, and the French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile, when investigators believe that this is warranted. These aspects of investigations affect the way in which investigations are conducted, by emphasizing the investigators' ability to complete the investigation in a timely manner (i.e., "getting the job done"), while simultaneously following rigorous rules of logic.

From Antecedent to Error to Accident

Assumptions

Several assumptions about operator error in complex systems form the foundation of the investigative approach of this book. These are

- The more complex the task, the greater the likelihood that an error will be committed.
- The more people involved in performing a task, the greater the likelihood that an error will be committed.
- People behave rationally and operate systems in a way to avoid accidents.
- Errors cannot be eliminated, but opportunities for error can be reduced.

Although the first two assumptions may seem rather obvious, some assume the contrary, that by adding steps and operators to a task the chances of error decrease. In fact, with certain exceptions, the opposite is true. As a task becomes more complex and more people are needed to perform it, opportunities for error increase. In addition, operators are rational in that they want to avoid accidents and operate systems accordingly. Those who mean to cause accidents in effect intend criminal acts, which call for a different investigative approach than that used in this book. It should be noted, however, that on occasion criminal acts have been initially investigated as accidents, until evidence of operator planning to make the event appear to be an accident emerged (e.g., National Transportation Safety Board, 2002).

Systems that people design, manage, and operate, are not immune to the effects of error. Because people are not perfect, designers and managers cannot design and oversee a perfect system and operators cannot ensure error-free performance. Operators of any system, irrespective of its complexity, purpose, or application, commit errors. As Gilbert, Amalberti, Laroche, and Paries (2007) observed,

> Observations of operators' practices show that they regularly make errors, which are therefore not abnormalities or exceptions. The errors are accepted, remedied or ignored. Errors are a price to pay, a necessity for adjustment, mere symptoms of good cognitive functioning. Errors (and all failures) can neither be reduced to departures from the rules, nor considered as abnormalities or exceptions. They are an integral part of habitual, normal functioning, irrespective of the level on which they are situated. (p. 968)

The task of investigators, therefore, is to determine the cause of errors so that modifications to the system can be proposed, so that the circumstances that led to the errors are prevented from recurring.

General Model of Human Error Investigation

Researchers have proposed different accident causation and investigation models, to explain how error affects operator performance in investigations. Some, like Leveson's (2004) systems-theoretic accident model and processes (STAMP) model, seek to integrate accident causation analysis with hazard analysis and accident prevention strategies. Others, like Shappell and Wiegmann's human factors analysis and classification system (HFACS) model (1997, 2001), which is directly based on Reason's model of error causation (1990, 1997), have been widely used to analyze the role of human factors in accident causation (e.g., Li and Harris, 2005; Schröder-Hinrichs, Baldauf, and Ghirxi, 2011).

However, models, largely because they are directly based on theory, may be difficult to apply in actual investigations. Accidents are unique events and investigators must be prepared to identify data to be collected and analyzed according to the needs of the investigation, rather than of particular theories. As Reason et al. (2006) note,

> Accidents come in many sizes, shapes and forms. It is therefore naïve to hope that one model or one type of explanation will be universally applicable. Some accidents are really simple, and therefore only need simple explanations and simple models. Some accidents are complex, and need comparable models and methods to be analysed and prevented. (p. 21)

Neville Moray (1994, 2000), a British human factors researcher, contends that error in complex systems results from elements that form the systems and to investigate system errors, one must examine the pertinent elements. He outlines these features with concentric squares that show the equipment as a core component of the system (Figure 3.2). These elements shape the system:

- Equipment
- Individual operator
- Operator team
- Company and management
- Regulator
- Society and cultural factors (Figure 2.2)

Each system component affects the quality of the system operation, and can create opportunities for operator error. For example, the information

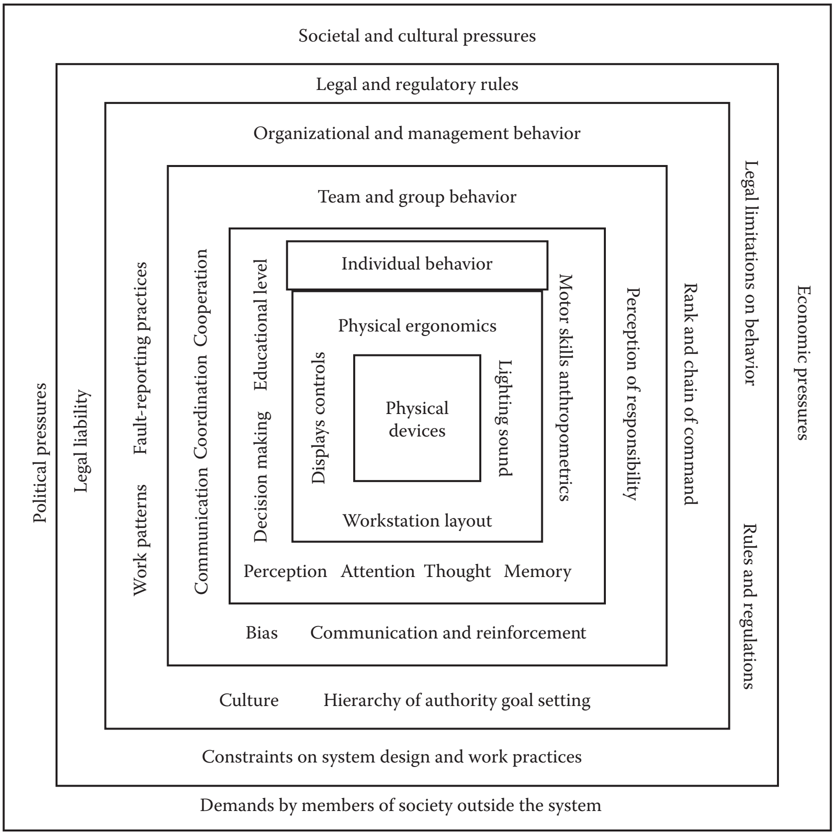

FIGURE 2.2
Moray's model of error. (From Moray, N. 1994. *Human error in medicine* (pp. 67–91). Hillsdale, NJ: Erlbaum; Moray, N. 2000. *Ergonomics*, *43*, 858–868. Copyright Taylor & Francis. Reprinted with permission.)

operators obtain about the system affects their perception of the system state. Displayed information that is difficult to interpret can increase the likelihood of error. Each of these elements can lead to error in itself, or can interact with the others to create opportunities for error.

To be useful for those investigating accidents, models must be practical and if not investigators will have difficulty applying them to investigations. Models should also be simple by avoiding complexity in explaining error or accident causation. For optimum benefit, models should also be practical, while still adhering to research findings on error causation. This text will eschew models in favor of a method that, based in the theories of both Moray (1994, 2000) and Reason (1990, 1997), is designed to facilitate the task of data identification, collection, and analysis for those investigating the role of human error in accident and incident investigations.

Antecedents

Because errors are unintended, one assumes that operators want to operate systems correctly. Using Moray's (1994, 2000) model, with that of Reason (1990, 1997), their errors are considered to reflect system influences on their performance. That is, the operators wanted to perform well but did not because of shortcomings within the system.

I refer to these characteristics as precursors or antecedents to error. As Reason argues, antecedents may be hidden within systems, such as in equipment design, procedures, and training, where they remain unrecognized but can still degrade system operators' performance. The mechanisms by which each antecedent or precursor exerts its influence varies with the context and nature of both the system element and the antecedent itself. For example, an antecedent may distract an operator during a critical task, hinder his or her ability to obtain critical information, or limit his or her ability to recall or apply the proper procedure. The focus of the accident investigator therefore should be to identify those shortcomings within the system that led to the accident.

Investigators identify the presence of an antecedent in two ways, by identifying an action, situation, or factor that influenced the operator's performance during the event, and more importantly, by obtaining evidence demonstrating that the operator's performance was affected by the antecedent. The evidence, which can take many forms, will be discussed in subsequent chapters.

Antecedents and Errors

Antecedents in complex systems contribute to errors through unrecognized or unacted upon shortcomings in the system. While complex systems are composed of a multitude of components, the elements of the system in this book are general, derived from the antecedents identified in both Moray (1994, 2000) and Reason's (1990) models. They can be considered latent errors or latent conditions within the system as well as system shortcomings, inadequacies, in sum, any other system action or decision that adversely influenced an operator's performance (Figure 2.3).

The errors that led to accidents and incidents, whether committed by operators or system managers, are either action errors, that is, someone did something wrong, or decision errors, that is, someone made a decision that proved to be erroneous. Further, because in accident causation failure to take an action or make a decision may be as critical to the cause of the accident as taking the wrong action or making a decision that proved to be erroneous, errors of omission should be considered as well as errors of commission.

The logic used in this process will be discussed in more detail in Chapter 3, Analyzing the Data. Keep in mind though, that the steps to be conducted in

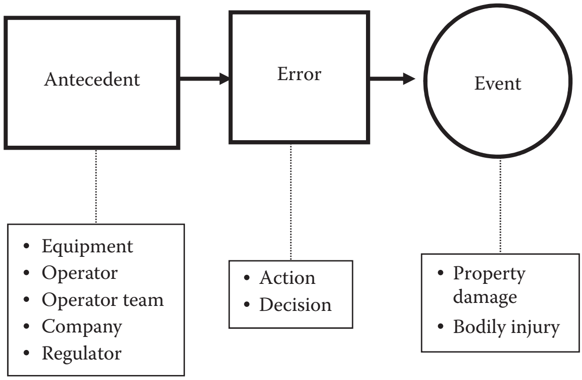

FIGURE 2.3
Error and accident causation in complex systems.

identifying both antecedents and errors, and relating them to the accident or incident, are ongoing through the investigation. That is, when identifying errors and searching for their antecedents, investigators should always keep in mind the role antecedents may play in the critical error or errors that led to the event under investigation.

Summary

Complex systems are those combinations of people, materials, tools, machines, software, facilities, and procedures designed to work together for a common purpose. Perrow argues that the interactive complexity and "tight coupling" or close interrelationships among complex system elements create conditions that make accidents and incidents "normal." When component malfunctions occur, the combination of interactive complexity and tight coupling within the system can create system states that neither operators nor designers had anticipated.

Error is defined as an action or decision that results in one or more unintended negative outcomes. Perrow's work has influenced theories of error, and has changed the way a system's influence on operator performance is viewed. Where researchers had seen errors as primarily reflecting on the person committing them, contemporary views of error see it originating within the operating system. Reason likens these elements to pathogens residing within the body. As pathogens can cause illness when certain conditions are met, system-related deficiencies (latent errors or latent conditions) cause the normal defenses to fail and lead to an operator error, which

causes an event. Moray delineates system elements that can lead to error in complex systems.

Error investigations can have many objectives and purposes, depending on the investigator's perspective. The objective of an investigation should be to mitigate future opportunities for error by identifying the critical errors and their antecedents, and eliminating them or reducing their influence in the system. The model of error that is proposed in the book describes six types of antecedents, each of which, alone or in combination, can adversely affect operator performance and lead to an error.

References

Brenner, C. 1964. Parapraxes and wit. In W. Haddon, Jr., E. Suchman, and D. Klein (Eds.), *Accident research: Methods and approaches* (pp. 292–295). NY: Harper & Row.

Chapanis, A. 1996. *Human factors in system engineering*. NY: John Wiley & Sons.

Coury, B. G., Ellingstad, V. S., and Kolly, J. M. 2010. Transportation accident investigation: The development of human factors research and practice. *Reviews of Human Factors and Ergonomics*, 6, 1–33.

Dekker, S. W. A. 2015. The psychology of accident investigation: Epistemological, preventive, moral and existential meaning-making. *Theoretical Issues in Ergonomics Science*, 16, 202–213.

Dekker, S. and Pruchnicki, S. 2014. Drifting into failure: Theorising the dynamics of disaster incubation. *Theoretical Issues in Ergonomics Science*, 15, 534–544.

Flin, R., Mearns, K., O'Connor, P., and Bryden, R. 2000. Measuring safety climate: Identifying the common features. *Safety Science*, 34, 177–192.

Gilbert, C., Amalberti, R., Laroche, H., and Paries, J. 2007. Errors and failures: Towards a new safety paradigm. *Journal of Risk Research*, 10, 959–975.

Heinrich, H. W. 1931. *Industrial accident prevention.* NY: McGraw-Hill.

Heinrich, H. W. 1941. *Industrial accident prevention* (2nd ed.). NY: McGraw-Hill.

Hollnagel, E. 1993. *Human reliability analysis: Context and control*. San Diego, CA: Academic Press.

International Civil Aviation Organization. 1970. *Manual of aircraft accident investigation* (4th ed.). Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization. 1993. *Human factors digest No. 7: Investigation of human factors in accidents and incidents*. ICAO Circular 240-AN/144. Montreal, Canada: International Civil Aviation Organization.

Kahan, J. P. 1999. Safety board methodology. In *Proceedings of the Second World Congress on Safety of Transportation*, February 18–20, 1998, pp. 42–50. Delft, Netherlands: Delft University Press.

Lawton, R. and Parker, D. 1998. Individual differences in accident liability: A review and integrative approach. *Human Factors*, 40, 655–671.

Le Coze, J. C. 2008. Disasters and organisations: From lessons learnt to theorizing. *Safety Science*, 46, 132–149.

Le Coze, J. C. 2013. What have we learned about learning from accidents? Post-disasters reflections. *Safety Science*, 51, 441–453.

Leveson, N. G. 2004. A new accident model for engineering safer systems. *Safety Science*, 42, 237–270.

Li, W. C. and Harris, D. 2005. HFACS analysis of ROC Air Force aviation accidents: Reliability analysis and cross-cultural comparison. *International Journal of Applied Aviation Studies*, 5, 65–81.

Loimer, H. and Guarnieri, M. 1996. Accidents and acts of god: A history of the terms. *American Journal of Public Health*, 86, 101–107.

Moray, N. 1994. Error reduction as a systems problem. In M. S. Bogner (Ed.), *Human error in medicine* (pp. 67–91). Hillsdale, NJ: Erlbaum.

Moray, N. 2000. Culture, politics and ergonomics. *Ergonomics*, 43, 858–868.

National Transportation Safety Board. 2002. Egypt Air flight 990, *Boeing 767-366ER, SU-GAP, 60 Miles South of Nantucket, Massachusetts, October 31, 1999*. Report Number AAB-02-01. Washington, DC.

Norman, D. A. 1981. Categorization of action slips. *Psychological Review*, 88, 1–15.

Norman, D. A. 1988. *The Psychology of Everyday Things*. NY: Basic Books.

O'Hare, D. 2000. The "Wheel of Misfortune": A taxonomic approach to human factors in accident investigation and analysis in aviation and other complex systems. *Ergonomics*, 43, 2001–2019.

Perrow, C. 1999. *Normal accidents: Living with high-risk technologies* (2nd ed.). Princeton, NJ: Princeton University Press.

Rasmussen, J. 1983. Skill, rules, and knowledge; Signals, signs and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man and Cybernetics*, 13, 257–266.

Rasmussen, J., Pejtersen, A. M., and Goodstein, L. P. 1994. *Cognitive systems engineering*. NY: John Wiley & Sons.

Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Reason, J. T., Hollnagel, E., and Paries, J. 2006. *Revisiting the "Swiss Cheese" model of accidents*. EEC Note No. 13/06, Brussels, Belgium: Eurocontrol.

Rodgers, M. D. and Blanchard, R. E. 1993. *Accident proneness: A research review*. DOT/FAA/AM Report No. 93/9. Washington, DC: The Federal Aviation Administration, Office of Aviation Medicine.

Schröder-Hinrichs, J. U., Baldauf, M., and Ghirxi, K. T. 2011. Accident investigation reporting deficiencies related to organizational factors in machinery space fires and explosions. *Accident Analysis and Prevention*, 43, 1187–1196.

Senders, J. W. and Moray, N. P. 1991. *Human error: Cause, prediction, and reduction*. Hillsdale, NJ: Erlbaum.

Shappell, S. A. and Wiegmann, D. A. 1997. A human error approach to accident investigation: The taxonomy of unsafe operations. *The International Journal of Aviation Psychology*, 7, 269–292.

Shappell, S. A. and Wiegmann, D. A. 2001. Human factors analysis and classification system. *Flight Safety Digest*, February, 15–25.

Stoop, J. and Dekker, S. 2012. Are safety investigations pro-active? *Safety Science*, 50, 1422–1430.

Sutcliffe, A. and Rugg, G. 1998. A taxonomy of error types for failure analysis and risk assessment. *International Journal of Human–Computer Interaction*, 10, 381–405.

Vicente, K. J. 1999. *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, NJ: Erlbaum.

Woods, D. D., Johannesen, L. J., Cook, R. I., and Sarter, N. B. 1994. *Behind human error: Cognitive systems, computers, and hindsight.* Wright-Patterson Air Force Base, OH: Crew Systems Ergonomics Information Analysis Center (CSERIAC).

3

Analyzing the Data

> As is so often the case when we begin to learn the complexities of a situation, some of the issues that had seemed very clear at the outset had become more confused. Only much later would we fully understand the extent to which oversimplification obfuscates and complexity brings understanding.
>
> **Vaughan, 1996**
> *The Challenger Launch Decision: Risking Technology, Culture, and Deviance at NASA*

Introduction

Most of us routinely make judgments from available data, perhaps without recognizing that we have done so. We examine the behavior of our friends, acquaintances, and political leaders and infer motives from their behavior to explain them. This process—examining an action and explaining it—is the foundation of the human error investigator's work.

Differences between this type of informal analysis and the more formal one used in error investigations result less from differences in the process than in the application. Unlike the informal process applied to everyday situations, investigative analysis is applied systematically and methodically. This chapter examines the principles of investigative analysis, the process in which error investigators identify relationships between operator errors and their antecedents.

Investigative Methodology

Accident investigation methodology and the scientific method have similar objectives, to explain observed phenomena or events by using formal methods of data collection and analysis. The objectives of scientific research correspond to those of accident investigations, "[the] systematic, controlled,

empirical, and critical investigation of hypothetical propositions about the presumed relations among natural phenomena" (Kerlinger, 1973, p. 11). Although control groups are not used in accident investigations and the process is not empirical, accident investigators apply a systematic and critical methodology to study the relationships between antecedents and errors, and the relationships among those errors, to determine the extent of the relationships, if any, between those errors and the incidents and accidents that the errors may have caused.

Ex Post Facto Designs

Investigators collect and analyze data after the fact, that is, after an accident has occurred, using a method that is similar to "ex post facto" research designs. Here, investigators work backward after the event has occurred and the data have been collected, to identify and explain the nature of the variables that led to the event. Ex post facto analytical techniques allow investigators to effectively explain the nature of the relationships underlying the data and apply them well beyond the immediate circumstances of the event under investigation. Well-conducted investigation analyses fall within Vicente's (1997) observation that, "science…encompass(es) naturalistic observation, qualitative description and categorization, inductive leaps of faith, and axioms that can never be empirically tested" (p. 325).

However, researchers have recognized that this method, although providing critical insights into event causation, can lead to analytical inaccuracy. Because data are gathered after the fact, researchers and investigators can select from and apply a favored explanation to account for the obtained results, rather than be compelled to accept the explanation that the data offer from experimental design techniques developed before the fact (e.g., Kerlinger, 1973). Dekker (2002, p. 374) and others refer to this as hindsight bias, a tendency in accident investigations to lead investigators to, as he writes, make "tangled histories" of what operators were dealing with at the time of an accident "by cherry-picking and re-grouping evidence" to fit their view of what transpired in the accident. However, knowledge of an operator's error and the accident that occurred as a result need not necessarily lead to highsight bias. In fact, investigators as a matter of course recognize that their job calls on them to explain errors from the perspective of the person who committed them, because doing so allows a proper analysis to be conducted of the system flaw that led to the error.

Nonetheless, error investigators compensate for this potential limitation because they typically obtain data on many measures, data that had been continuously collected throughout the event, unlike researchers who generally collect data on only a few parameters, often only at selected intervals, and under highly controlled conditions. Further, investigators examine real world behavior under conditions that could not reasonably be examined in controlled settings. Thus, by collecting considerable data about an event,

subjecting the data to objective and systematic analysis, and by being sensitive to the possibility of hindsight bias, investigators can avoid allowing hindsight bias to affect their analyses.

Imprecision

The logic of error investigations assumes a direct relationship between one or more system deficiencies or shortcomings, and the critical error or errors that led to an accident. The previous chapter described the basic model that this text follows, that is, antecedent leading to error, which then leads to an accident; subsequent chapters will describe the particular antecedents that investigators need to examine, and their potential influence on operator performance.

Although the investigative process is systematic, it is still affected by the skills and experience of the particular investigator. For this and other reasons, some have shied away from definitive identifications of accident "causes." As noted in Chapter 2, "there is no absolute cause" of an accident because imprecision is an inherent part of error investigations. Absolute certainty in establishing the errors leading to an event is an impossibility.

Klein, Rasmussen, Lin, Hoffman, and Cast (2014) referred to the explanation of behavior as "indeterminate causation," which, as they write, "is involved in the anticipation or explanation of human belief and activity" (p. 1381). Moreover, they note then when dealing with explanations of events involving human behavior, for example, why a sports team lost,

> …no amount of analysis can establish the "actual" cause or single cause or "root" cause. There are no single or uniquely correct answers to such questions, and no amount of research would uncover the one "real" cause or the "objective" cause, because there is no such thing. (p. 1381)

As a result, some investigative agencies use the term "probable cause" of an accident rather than the more succinct and absolute "cause," acknowledging that, despite their best investigative and analytical efforts, the influence of an unidentified variable remains a possibility. Some agencies do not use the term "cause" at all in their investigations but list findings instead, as does the Australian Transport Safety Bureau (2007). Some have criticized the use of any type of cause in an investigation. Miller (2000), for example, suggests that this,

> Relates back to a subject pursued for the past quarter century or so—that detestable preoccupation most people seem to have with "cause." If investigative processes and classifications of accident findings continue to be hung up on "cause" instead of pursuing the implementation phase [of remediation strategies and techniques] further, we are going to be static at best in prevention efforts. (p. 16)

Yet, differences in the results of incident and accident investigations between organizations that determine a cause and those that do not suggests little difference between them. Whether an organization determines a probable cause or not appears to make little difference to the quality of the investigation or its proposed recommendations. Irrespective of a requirement to develop a cause to an event, the key focus for investigators should be on conducting a thorough and systematic investigation in order to reduce future opportunities for error. Doing so will result in effective investigations, regardless of the nature of the "cause" or "findings" that are determined. As Klein et al. (2014) note, "regardless of which causes are invoked, an explanation has to adopt a format or argument structure for characterizing these causes" (p. 1381).

An Illustration

A hypothetical accident illustrates the process. Assume that a train failed to stop at a stop signal (also referred to as an "aspect") and struck another train that had been standing on the same track. The locomotive engineer had an unobstructed view of the signal.

The engineer claimed that he observed a stop signal and applied the brakes, but the brakes failed. If he is correct, investigators will have to identify a mechanical malfunction as the cause of the accident, otherwise they would unfairly fault an operator who performed well, and worse from a safety consideration, fail to address hazards that led to the accident in the first place. However, before they could accept the engineer's explanation as the most likely cause of the accident, investigators would have to test and accept the viability of several possible conclusions that are necessary to accept a failed brakes explanation. These are

1. The brakes were defective at the time the engineer claims to have applied them
2. Brakes with this defect would be unable to stop a comparable train traveling at the same speed, in the same distance, on the same track section
3. Other possible malfunctions that could also have failed to stop a comparable train traveling at the same speed, in the same distance, on the same track section, were not identified

Thus, investigators are faced with only two possible alternatives to the cause of the accident, assuming that signals, track, and other train systems were not involved. Either the engineer failed to properly apply the brakes, or he applied them correctly but a mechanical malfunction prevented the brakes from stopping the train. To determine which of these conclusions is supported, investigators would need to collect a variety of system data. If the data supported these conclusions, they could be reasonably confident that

defective brakes caused the accident. If not, other explanations would need to be proposed, and the data reexamined and reanalyzed. The data would either support or refute the proposed explanations.

Analysis Objectives

As discussed in Chapter 2, investigators bring their own perspectives to the analysis, depending upon their employer, their values, and the like. The investigation objective that is endorsed in this text is, *to identify the errors and their antecedents that led to the occurrence being investigated, so that future opportunities for error can be reduced or eliminated*. Investigators should examine the collected data to meet this objective until they are confident that the identified relationships conform to criteria that will be discussed shortly.

During an investigation, it is likely that investigators will collect different types of data of varying quality. Before analyzing the data, they evaluate the collected data to assess their value in the investigation. Not all data are of equal value and some types of data should be given more consideration than other types.

Assessing the Quality of the Data

Some of the data that investigators collect will pertain to the investigation objective while other data may not; some data sources will be complete and others not. Including incomplete data and data that do not address the antecedents of error in the analysis will lead to an analysis that contributes little to understanding the origin of the particular errors, or worse, is incorrect.

Determining the quality of data is critical because the effectiveness of an investigation largely depends on the quality of the data that investigators collect. "Garbage in-garbage out" applies to the analysis of error in incidents and accidents as it does to other types of analysis. Two standards of quality are used to assess data value, internal consistency and sequential consistency.

Internal Consistency

Anderson and Twining (1991), describing legal analysis, believe that internally consistent data should converge into one conclusion. Converging data, they argue, even if derived from different sources and collected at different times, support the same conclusion. For example, if an operator's performance history reveals deficiencies and those deficiencies are similar to characteristics of the operator's performance at the time of the occurrence, the data converge. In that instance, one could reasonably conclude that the operator's performance during the event was consistent with his

performance in previous, similar circumstances and not an aberration. In complex systems, internally consistent data converge by depicting different aspects of the same event similarly, at the same points in time. If they do not, the data will not be internally consistent.

In the hypothetical railroad accident in which defective brakes are suspected of having caused the collision, one can assume that at a minimum, investigators will collect data regarding

- The operator's train orders and his or her interpretation of them
- The operator's speed, power, and brake application commands
- The actual train speed, power, and brake settings
- Pertinent operating rules, procedures, and operating limitations
- The operator's training and performance record
- Toxicological analysis of specimens of the operator
- The operator's sleep/wake history before the accident
- The operator's medical history and medication use
- The commanded and displayed signals
- Lights, flags, or markings at the aft end of the standing train
- Company oversight of its operations
- The regulator's history overseeing the railroad

If the brakes had been defective and investigators determined that the defect caused the accident, internally consistent data should reveal the effects of the defect among a variety of types of data. All data, except those pertaining to the brakes and those independent of the sequence of antecedents and errors/flaws leading to the event, should be consistent. However, if the data showed defects in other components that could have altered the sequence of occurrences, or if the brakes were found to have been defect free, the data would be inconsistent and the discrepancy would need to be resolved.

Inconsistencies could be caused by deficiencies either in the data or in the proposed theory or explanation of the cause of the event. Deficiencies in the equipment-related data could result from flaws in the recording devices, measuring instruments, or, with eyewitnesses, in their perceptions and recall of the event. Inconsistencies in operator-related data could be caused by any of several factors that will be discussed shortly. Otherwise, inconsistent data indicate the need to revise the theory or explanation of the cause of the accident, to reexamine the data, or to collect additional data.

Likely sources of inconsistent data. Inconsistencies among the data, though rare, are most often found among eyewitness accounts and operator-related information. Substantial differences among eyewitness accounts are infrequent, but, as investigators found in the explosion of the Boeing 747 off the

coast of Long Island, occur occasionally (National Transportation Safety Board, 2000a). Inconsistencies in eyewitness data largely result from perceptual and memory factors, and from differences in interviewer techniques, topics that will be discussed in Chapter 11.

Several factors may explain differences in operator-related information. For one, people interact differently with operators than they do with others, based on their relationships with them. Colleagues, acquaintances, and supervisors have different perceptions of the operator than would his or her family members, and these perceptions will affect the information they give interviewers. In addition, as discussed in Chapter 14, changes that occur over time in such parameters as measures of operator performance and health may also lead to inconsistent data.

Investigators can safely discard inconsistent data, if the inconsistency is not a result of deficiencies in the way the data were collected and if it can be safely attributed to factors related to investigation shortcomings or to the event itself. Investigators of the 1999 collapse of logs being prepared for a bonfire at Texas A & M University that resulted in 12 deaths, discarded numerous eyewitness reports that were not supported by the physical evidence, or were otherwise irrelevant (Packer Engineering, 2000; Special Commission, 2000). As investigators, who used the term Bonfire to refer to the stack of logs, describe,

> A large number of interview summaries prepared by Kroll [the organization that conducted the interviews] contained information which was either not in agreement with the physical evidence, or not directly related to the Bonfire collapse. These summaries were not included with Packer's [the organization that conducted the physical examination of the logs and the] analysis. Of the remaining summaries, those containing information from witnesses who were physically on Bonfire at the time of the collapse were considered most accurate, while those of witnesses at Bonfire but not on the actual stacks were also considered highly accurate. (Packer Engineering, p. 25)

Because the physical evidence contradicted many of the eyewitness accounts, and because the inconsistencies between the eyewitnesses reports and the other data did not result from factors related to the event or investigation shortcomings, investigators could confidently discard the inconsistent eyewitness data without affecting the quality of the subsequent analysis and the strength of the findings and conclusions.

Sequential Consistency

Investigative data should consistently match the sequence of occurrences and the period of time in which they occurred. The sequential relationships between antecedents and errors are invariant; antecedents will always precede errors and errors will always precede the event.

In the railroad accident example used earlier, if a signal commands a stop, locomotive event recorders would be expected to show, in order, power reduction first and then brake application, corresponding to the order of the expected operator actions. The data should also match the passage of time corresponding to the occurrence, in the actual period in which the train approached the signal and struck the standing train. Regardless of the rate at which actions occur and system state changes, the two should correspond. Specific operator actions must still occur in certain orders and within specific periods of time, after certain events have taken place. Further, specific operator actions should precipitate specific equipment responses.

Sequentially inconsistent data may be the result of inaccurate data recorders, defective measuring devices, or deficiencies within the data. If the inconsistencies cannot be resolved satisfactorily, investigators may need to collect additional data, or reexamine the data selection and collection methods to resolve the inconsistencies.

Data Value

Data vary in their value and contribution to the investigation. Depending on the event and the data, investigators may rely on some data to understand what happened and why and ignore other data. The greater the reliability, accuracy, and objectivity of the data, the greater their value to, and influence upon, the analysis. Reliable and objective data from different sources should describe the same phenomenon the same way, albeit from different perspectives, regardless of their sources.

In general, "hard" data, data obtained directly by the system, contribute substantially to the investigation because of their high reliability, objectivity, and accuracy. By contrast, the value of "soft data," such as eyewitness accounts and interview data, is less because the data can change as a function of the person collecting the data, the time of day the data are obtained, and the skill of the interviewer or person collecting the data, among other factors.

Relevance

Anderson and Twining (1991), referring to legal analyses, consider a statement relevant if it tends to make the hypothesis to be proven more likely to be supported than would otherwise be the case. Data that can help explain conclusions regarding the cause of the event, the critical errors, and the antecedents to the errors, are analogous to data that can support the hypothesis and are considered relevant to the investigation.

Most investigators routinely gather data that may not necessarily relate to their investigations but are needed to rule out potential explanations or

factors. If it is determined that an operator did not commit an error, one can exclude data from the analysis that pertains to the operator's performance history without degrading the quality of the analysis or the investigation, unless the data relate to other critical issues. On the other hand, if operator error is believed to have led to the incident, almost all data concerning the operator would be considered relevant and therefore would be included in the analysis.

Data relevance can change as more is learned about an event. For example, an initial focus on potential training deficiencies makes information pertinent to the development, implementation, and conduct of the training relevant to the investigation. If the data suggest that equipment design factors rather than training affected operator performance, operator training-related data would be less relevant.

Quantity

The more data obtained about a particular aspect of the system, the more confidence one can have in the value of the data and their contribution to the analysis. For example, in some systems, multiple recorders capture a variety of operator performance parameters, documenting the operator's spoken words and any related sounds. These provide a considerable amount of data that describe, both directly and indirectly, what the operator did before and during the event.

If there are little data available, other measures that can approximate the parameters of interest should be sought. If no data directly describe aspects of operator performance, investigators may need to learn about operator actions from other sources, such as from system recorders. If there are insufficient data available to allow inferences about the parameters of interest, conclusions regarding the data of interest will have little factual support.

Identifying the Errors

After the data have been examined and evaluated, one can begin to propose relationships among antecedents, errors, and the causes of the event.

The Sequence of Occurrences

To begin developing the critical relationships, first establish the sequence of actions and occurrences in the event. The sequence will determine the order of actions and decisions, and facilitate the task of identifying the critical relationships.

Establish the sequence of occurrences in the event by working backward from the event itself until the errors that led to the event, and the antecedents

to those errors, are reached—what Rasmussen, Pejtersen, and Goodstein (1994) refer to as the "stopping point." Regardless of the event, whether an airplane accident, chemical refinery explosion, or vessel grounding, stop collecting data and analyzing the data at the point at which the sequence of occurrences that led to the incident or accident begins.

Using the railroad accident discussed earlier, the sequence of occurrences begins with the collision. Working backward from the event, occurrences earlier in the sequence would likely include the engineer's brake application and power reduction, and progress to company brake maintenance practices, going as far back as brake manufacture and locomotive assembly.

The sequence of occurrences includes major system elements. In this illustration, these would include the operator, the railroad, the regulator, and the brake system. However, a few issues should be ruled out early in the investigation. Data pertinent to those issues need to be collected to determine the role of each element in the event.

For example, if it is learned that the locomotive engineer did not apply the brakes properly, then operator actions would be a focus of the investigation and investigators would need to identify potential antecedents to those actions. Other issues to be investigated would likely include the railroad's training and oversight of its operators, and the regulator's oversight of the railroad. Although each accident is unique with its own set of occurrences, the critical facts, in this instance the collision, the record of inspections of the brakes and their manufacture, would not be in dispute. A list of an initial sequence of occurrences of the hypothetical railroad accident is illustrated below.

Sequence of Occurrences—Beginning with the Collision

1. The collision
2. Locomotive operator brake application
3. Locomotive operator power reduction
4. Railroad signal system maintenance and inspection
5. Locomotive operator initial and refresher training
6. Railroad brake system maintenance and inspection
7. Railroad brake system maintenance personnel selection practices
8. Brake system manufacture and installation
9. Railroad signal system selection and acquisition
10. Signal system manufacture
11. Railroad signal system selection and installation
12. Railroad signal installer, maintenance, and inspection personnel training
13. Locomotive operator selection
14. Railroad brake system maintenance personnel selection practices

15. Railroad signal system installer, maintenance, and inspection personnel selection practices
16. Regulator oversight of railroad signal system
17. Regulator oversight of brake system

Let's assume that in this example, after interviewing critical personnel and collecting and examining the data, investigators determine that the operator performed satisfactorily. In that case, data relating to operator performance history can be safely excluded from the sequence of occurrences and from subsequent data analysis. The results of a second iteration of a sequence of occurrences, after first discarding occurrences irrelevant to the issues of interest can be seen in the list below.

Events Excluded

1. Locomotive operator brake application
2. Locomotive operator power reduction
3. Locomotive operator initial and refresher training
4. Locomotive operator selection

Events Retained

1. The collision
2. Railroad signal system maintenance and inspection
3. Railroad brake system maintenance and inspection
4. Railroad brake system maintenance personnel selection
5. Brake system manufacture and installation
6. Railroad signal system selection and acquisition
7. Signal system manufacture
8. Railroad signal system selection and installation
9. Railroad signal installer, maintenance, and inspection personnel training
10. Railroad brake system maintenance personnel selection practices
11. Railroad signal system installer, maintenance, and inspection personnel selection practices
12. Regulator oversight of railroad signal system
13. Regulator oversight of brake system

The Error or Errors

After examining the data, assessing their relative value, and establishing the sequential order of occurrences, investigators can exclude from the analysis

several additional factors that would no longer be considered relevant to the accident. For example, if tested and found to have been in acceptable condition at the time of the event, factors related to the signal system may now be considered irrelevant.

The next step in the data analysis can now be conducted, identifying the errors that led to the event, perhaps the most critical step in the analysis. This step is distinct and separate from the formal or legal determination of the accident cause. The focus should be on the errors suspected of leading to the event.

Assessing the Relationship of Antecedents to Errors

After identifying the errors, the antecedents of those errors must be determined. The process is largely inferential, based on investigative logic regarding the relationship between the two. The evidence consists of the nature of the error, and information from written documentation, interviews, system recorders, equipment, and other sources.

Inferring a Relationship

A relationship between antecedent and error must be logical and unambiguous. Investigators must establish that the antecedent, either by itself or with others, influenced the operator's performance so that he or she committed an error. To identify the antecedent, one should ask a counterfactual question, would the operator have committed the error if this (and other) antecedent(s) had not preceded it? If the answer is no, one could be confident that the antecedent led to the error. Counterfactual questions are central to analyzing error data in investigations.

Assume that insufficient operator experience is one of several antecedents that affected the performance of an operator, and the operator misinterpreted system-related data as a result. A relationship between experience in operating a system and the error of misinterpreting data is logical; a more experienced operator is less likely to commit the same error than a less experienced one. This conclusion is supported by research findings and the determinations of previous accident investigations. This relationship between antecedent and error is clear and unambiguous, reached only after the necessary facts have been obtained and analyzed.

Statistical Relationship

The logic used to establish a relationship between antecedents and errors is analogous to multiple regression analysis, a statistical technique used to

determine the relationship between one or more predictor variables and a single variable (e.g., Harris, 1975). Economists, for example, employ multiple regression analysis to predict the combined effects of changes in variables such as the prime interest rate, unemployment, and government spending, or changes in an outcome variable such as inflation rate.

The stronger the relationship between the predictor or influencing variables and the outcome variable, the higher the *correlation* between the two sets of variables. In relationships that have high positive correlations (say 0.60 or higher since correlations of plus or minus one are the limits of correlational strength), changes in the predictor variables are associated with corresponding changes in the outcome variables. As the value of predictor variables increases or decreases, the value of the outcome variable similarly increases or decreases. If the correlations are negative, predictor variable changes in one direction would be associated with outcome variable changes in the opposite direction. As the predictor variables increase or decrease in value, the outcome variable loses or gains value in the opposite direction.

Multiple regression analyses also describe another facet of these relationships that can be stated statistically; when the correlation between the two sets of variables is high the predictor variables account for much of the total variance in changes in the outcome variable. That is, the higher the correlation between the two, the more that changes in the predictor variables—and not some other variable or the effects of chance—are associated with changes in the outcome variable. The lower the correlation, the less that changes in the outcome variable can be attributed to changes in the predictor variables. In that case, changes in the outcome variable will more likely be associated with variables that had not been considered in the analysis.

In investigations of error, the predictor variables correspond to the antecedents and the outcome variable to the critical error. Investigators assess the relationship between one or more antecedents and the operator's error in the circumstances that prevailed at the time of the accident. The stronger the relationship between the antecedents and errors, the more the antecedents would account for "variance" about the errors, and the more the error can be attributed to those antecedents, and not to other variables or antecedents not yet recognized.

Relating Antecedents to Errors

In short, and as mentioned, relationships between antecedents and errors need to meet three critical criteria; (1) they should be simple, (2) logical, and (3) superior to other potential relationships among the variables. These criteria are related; if a relationship meets one criterion, it will likely meet the others as well.

The influence of an antecedent variable on the error should be as simple as possible. One should be directly related to the other, with as few assumptions

as possible needed to support it. A simple relationship should also be logical, one that makes sense to all concerned. It should require little analytical effort to understand the relationship between one and the other. In addition, it should be simpler and more logical than other, alternative proposed relationships.

Counterfactual Questions

To determine with confidence that a proposed error has contributed to the cause of the event, ask a counterfactual question; would the accident have occurred if this error had not been committed? If the answer is no, the accident would not have occurred, one can be confident that the error caused or contributed to the cause of the accident.

Using the train collision illustration, assume that (1) the brake defect resulted from a maintenance error and (2) the defect was sufficiently conspicuous that inspectors should have noticed it during routine inspections, but they did not. In addition to the errors of those involved in the brake maintenance, the investigation would also examine the inspectors' errors and consider them contributory to the accident. In this accident, if neither error had been committed, the accident would not have occurred. Both errors are needed for the accident to occur, and each can be considered to have led to the accident. If the maintenance error has been identified, the list of relevant occurrences to be retained can be further narrowed, with a concomitant expansion of the list of those excluded, as illustrated below. This list includes the accident itself, the errors that directly led to it, as well as the antecedents that may have allowed the errors to occur.

Events Excluded

1. Locomotive operator brake application
2. Locomotive operator power reduction
3. Railroad signal system maintenance and inspection
4. Locomotive operator initial and refresher training
5. Railroad signal system selection and acquisition
6. Signal system manufacture
7. Railroad signal system selection and installation
8. Railroad signal installer, maintenance, and inspection personnel training
9. Locomotive operator selection
10. Railroad signal system installer, maintenance, and inspection personnel selection
11. Regulator oversight of railroad signal system

Events Retained

1. The collision
2. Brake system manufacture and installation
3. Railroad brake system maintenance and inspection
4. Railroad brake system maintenance personnel training
5. Railroad brake system maintenance personnel selection
6. Regulator oversight of brake system

Multiple Antecedents

In complex systems, multiple antecedents often influence operator performance. Multiple antecedents can affect performance cumulatively, by increasing the influence of each to bring a greater total influence on operator performance than would otherwise be the case, and they can interact with each other to differentially affect performance. Investigators should search for the presence of multiple antecedents, even if one antecedent appears to adequately explain the error.

Cumulative Influence

Multiple antecedents can increase each antecedent's influence on operator performance so that their cumulative total influence is greater than would otherwise be true. For example, individual antecedents of fatigue can cumulatively influence performance beyond that of individual antecedents, as investigators found in a 1998 accident involving a commercial bus. The bus driver fell asleep while at the controls, and the bus ran off the road and struck a parked truck as a result (National Transportation Safety Board, 2000b).

Investigators identified three antecedents of the driver's fatigue. Individually, each may have been insufficient to have caused him to fall asleep while operating the vehicle, but combined, their effects were substantial. Toxicological analysis of a specimen from the driver's body revealed the presence an over-the-counter sedating antihistamine that he had consumed earlier to treat a sinus condition. He had also worked at night for several consecutive days before the accident, after having maintained a daytime awake/nighttime asleep pattern, a schedule change that had disrupted his sleep patterns and caused a sleep deficit. Further, the accident occurred at 4:05 a.m., a time when he would ordinarily have been in his deepest phase of sleep. Those who stay awake at that time are especially prone to the effects of fatigue. Combined, the effects of the sedating antihistamine, disruptive

schedule, and time of day were sufficiently powerful that the driver was unable to stay awake.

Interacting Antecedents

Interacting antecedents can differentially affect operator performance. That is, two or more antecedents together will affect performance differently than the antecedents would have if acting on their own. To illustrate, assume that the control rooms of two electrical power generating stations, designed 5 years apart, are identical in all respects except that one employs "older" analog gauges and the other "newer" digital displays to present system information. The same information is shown in both, and in both generating station operators have received identical training and use identical procedures.

The operators of the two generating stations also have different levels of experience; one group has an average of 10 years of experience and the other, 2 years. Thus, four different operator/equipment groups are possible:

1. Experienced operators with "old" analog displays
2. Inexperienced operators with "old" analog displays
3. Experienced operators with "new" digital displays
4. Inexperienced operators with "new" digital displays

Further, in a certain nonroutine situation, the displays present information that requires the operators to respond. Only one of two responses is possible for that situation, either correct or incorrect. With no interaction, differences in operator response would be affected either by their experience or by the display type, or there would be little or no difference in their responses. Inexperienced operators might respond erroneously while experienced ones would not, or operators working with the "newer" displays could respond correctly though the others not. Alternatively, with no interaction all four groups could perform correctly or all could commit errors, in which case the effects of either operator experience or display type would lead to performance that is independent of the other. Figures 3.1 through 3.5 illustrate five of the possible outcomes.

An interaction occurs when experience and display type interact to differentially affect operator performance. Operators committing the greatest number of errors could be the inexperienced ones who worked with the "older" displays. Alternatively, experienced operators working with the "newer" technology could commit the greatest number of errors, and the inexperienced operators working with analog displays, the fewest.

The variety of human behavior, the diversity among procedures, training, and equipment, and the numerous component interactions within complex systems are such that the potential number of interacting antecedents

	Experienced	Inexperienced
Analog	Correct	Incorrect
Digital	Correct	Incorrect

FIGURE 3.1
Noninteracting antecedent: Operator experience.

	Experienced	Inexperienced
Analog	Correct	Correct
Digital	Incorrect	Incorrect

FIGURE 3.2
Noninteracting antecedents: Display type.

	Experienced	Inexperienced
Analog	Incorrect	Incorrect
Digital	Correct	Correct

FIGURE 3.3
Noninteracting antecedents: Display type.

	Experienced	Inexperienced
Analog	Incorrect	Correct
Digital	Correct	Incorrect

FIGURE 3.4
Interacting antecedents: Experience and display type.

	Experienced	Inexperienced
Analog	Correct	Incorrect
Digital	Incorrect	Correct

FIGURE 3.5
Interacting antecedents: Experience and display type.

that could affect performance is practically infinite. For example, training can interact with procedures or operating cycles so that certain types of training, say on-the-job training and classroom lectures, lead to different levels of performance, according to the particular procedure and operating cycle. Oversight may interact with managerial experience so that certain types and levels of oversight lead to superior operator performance.

Less experienced operators may perform best with extensive oversight, and experienced operators may perform best with little oversight. Some operators may perform effectively with certain types of controls, but erroneously with others, according to the type of training they receive. Because of the possible presence of interacting antecedents, investigators should continue as long as reasonably possible to continue searching for error antecedents, after identifying one or two that appear to have played a role in the error in question.

Concluding the Search for Antecedents

Despite thorough evidence gathering and sound analysis, investigators may experience some uncertainty regarding the antecedents that were identified. "Did I overlook something?" is a question that investigators often ask themselves. Statistical and experimental design techniques aid empirical researchers to reduce the role of unidentified variables, but even these techniques cannot exclude the possibility that something not identified influenced the obtained results. Researchers strive to control the variables they could identify, but because unidentified variables may always be present, absolute certainty is not possible. Rather, researchers rely on tests of statistical probability, in which the influence of randomly acting variables is measured and, if sufficiently low, acknowledged but considered sufficiently unlikely as to be absent.

Accident investigators must also acknowledge the possibility that antecedents that they had not identified contributed to the critical errors. Unidentified antecedents are always potential factors in investigations. Nevertheless, investigators can be confident that with methodical data gathering and thorough and objective analysis, they can minimize the possible effects of unidentified antecedents. Systematically and logically examining the effects of antecedents that are believed most likely to have influenced the probable errors, using investigative processes to determine the role of antecedents in error, and relying on empirical research and previous investigation findings to support the role of antecedents in error causation minimizes the likelihood that unidentified variables will be missed.

Sound analytical techniques also enable investigators to recognize when they have reached the point at which the search for antecedents should be stopped. Earlier in this chapter, the "stopping point," the point at which the search for antecedents should be ended, was discussed. For the purposes of this text, *the stopping point is reached when investigators can no longer identify antecedents that can serve as the target of remedial action*. Theoretically, the search for antecedents is infinite and investigators can never be certain that they have identified all possible antecedents. Investigators should pursue all issues and seek to identify all potential errors and antecedents. However, at some point, the increase in precision needed to understand the origin of the errors or mechanical failures is not worth the expending

of additional resources. When reaching the point at which logic dictates that little further activity will be worthwhile, further investigative activity becomes unproductive.

For example, suppose investigators identify deficient regulator oversight as a factor in the defective brakes, used in the previously discussed example. They determine that with effective regulator surveillance, deficiencies in the railroad's oversight would have been identified, the deficiencies corrected, and the defective brakes likely identified and repaired. However, the regulator could argue that it performed the best oversight it could with its limited resources. It could contend that it does not determine the number of its inspectors, rather, that Congress or Parliament makes that determination in its legislation. Of course, that is taking the search for antecedents to its ultimate conclusion. Pursuing the argument to that point is untenable if for no other reason than no agent could be identified that could implement effective remediation strategies. Before that point the investigation will have passed the point of diminishing returns, with little additional benefit gained from further activity.

Recommendations

After determining the relationships between errors and antecedents, identify the recommendations needed to mitigate future opportunities for error, the final step in the investigative analytical process. Many investigative agencies propose recommendations as the vehicle for strategies and techniques to correct system deficiencies that they have identified. Others use other means, but for the purpose of this text, the term "recommendations" will be used to describe proposed remediation strategies.

Recommendations accomplish a major objective of error investigations, to address and mitigate the system deficiencies or antecedents that led to the operator errors identified in the investigation, to reduce future opportunities for error. Recommendations describe at least two separate, but related entities, (1) the system deficiency and its adverse effects on safety and (2) the proposed remediation strategy or technique to correct the deficiency and improve safety.

Recommendations begin with an explanation of the deficiency and its adverse effects on safety. When referring to error, deficiencies are the antecedents to errors, but deficiencies can also be mechanical malfunctions, design failures, or other system defects. In general, three types of system deficiencies are the subject of recommendations; those that (1) led to the accident, (2) contributed to the cause of the accident, or, (3) were identified as system safety deficiencies, but were not involved in the cause of the accident.

The example of the rail accident cited earlier, in which inspectors failed to detect a flaw in the system, can illustrate how to develop recommendations. Suppose that investigators identified these deficiencies regarding inspector performance in failing to recognize the defects in the brakes,

1. Inspector fatigue from abrupt scheduled shift changes
2. Inappropriate inspector expectancy from having inspected flawless components exclusively
3. Inadequate inspection station illumination
4. Inadequate inspection procedures
5. Defective equipment

Recommendations can be proposed to address each of the safety deficiencies. Because the regulator and the company can correct each deficiency, the recommendations can be directed to either one. However, addressing recommendations to the regulator would, in effect, direct them to all organizations that the regulator oversees. If similar deficiencies are present at other companies, the regulator would implement or require corrective action with regard to those organizations as well in response to the recommendation. For the sake of simplicity, the recommendations used in the illustration will be directed to the regulator.

Investigators can take many directions in proposing recommendations. They can suggest specific solutions or leave it to the recipient of the recommendation to develop its own strategies to address the deficiency. The latter method is often preferred since it gives the recipient the latitude to develop corrective actions that meet its own needs, so long as investigators are satisfied that the corrective actions will be effective and meet the intent of the recommendation.

To develop a recommendation that addresses the first deficiency or antecedent, fatigue from an irregular work schedule, investigators can ask the regulator to revise its rules governing scheduling practices to prevent abrupt changes in shift schedules. Other recommendations, such as requiring companies to provide adequate rest periods before scheduling operators for night work, informing operators of the nature of fatigue and its effects, and providing information to both supervisors and operators to help them recognize operator fatigue, can also be made.

The second deficiency, expectancies from dealing with flawless components, can be corrected by requiring companies to, randomly and without notice, include in the items to be inspected, brake systems with recognizable defects, to increase the likelihood of inspectors encountering defects, and thus reduce their expectations of flawless parts. This action would have the additional benefit of creating a mechanism for both companies and operators to identify potential inspection problems.

To address the third deficiency, inadequate illumination, investigators can recommend that the regulator require companies to install adequate lighting in inspection stations. A recommendation to address the fourth deficiency, inadequate company inspection procedures, could be corrected by requiring companies to review existing procedures, identify the inadequacies, and develop procedures that address them. The fifth deficiency, defective equipment, could be rectified by requiring companies to examine their inspection equipment and replace or repair those items found to be defective. The proposed recommendations address specific antecedents to acknowledged errors, by identifying the deficiencies and proposing either general or specific corrective actions to the proper recipient.

Summary

Analyzing error data in accident investigations is similar to conducting empirical research; both apply formal methods of inquiry to explain relationships within data. In a human error investigation, the relationships under study are those between errors that led to an occurrence and the antecedents that led to the errors.

Human error investigators usually collect a substantial amount of data. However, only internally and sequentially consistent data should be included in an analysis. Data that do not meet these standards may have to be discarded, additional data obtained, and hypotheses revised to account for the inconsistencies.

The sequence of occurrences of the event is determined by working backward from the event to identify critical errors, and the antecedents that influenced the errors. Relationships between antecedents and errors should meet standards of simplicity, logic, and superiority to alternative relationships, and establish that without one the other would not have occurred. Investigators should then answer counterfactual questions to determine the role of the operator error or errors in an accident's cause, and the role of antecedents in error causation. Investigators should also consider the potential presence of multiple antecedents after identifying key error antecedents. Multiple antecedents can cumulatively increase each other's combined influence on operator performance, or interact to differentially affect performance.

After identifying the antecedents, investigators should develop recommendations to address safety-related deficiencies identified in the investigation. These will include the identified antecedents as well as safety deficiencies that were identified but which may not have been antecedents to the errors involved in the cause of the event. The recommendations should identify the deficiencies and suggest ways to mitigate them.

HELPFUL TECHNIQUES

- Discard data that do not meet standards of internal consistency, sequential consistency, reliability, objectivity, and accuracy, and if necessary, collect new data or revise the prevailing hypotheses.
- Determine the relevance of the data to the circumstances of the event, the critical errors, and the antecedents to the errors.
- Establish a sequence of occurrences by working backward, beginning with the final phase of the accident sequence and progressing to the errors that led to the event and their antecedents.
- Identify errors by asking, "Would the accident occurred if this error had not been committed?"
- Identify antecedents by asking, "Would the operator have committed these errors if these antecedents had not preceded them?"
- Establish relationships between antecedents and errors that are simple, logical, and superior to other potential relationships.
- Propose recommendations, after identifying errors and antecedents, that identify system deficiencies and suggest remediation techniques.

References

Anderson, T. and Twining, W. 1991. *Analysis of evidence: How to do things with facts based on Wigmore's Science of Judicial Proof*. Evanston, IL: Northwestern University Press.

Australian Transport Safety Bureau. 2007. *Analysis, causality, and proof in safety investigations*. Report No. AR-2007-053. Canberra, Australia: Australian Transport Safety Bureau.

Dekker, S. W. A. 2002. Reconstructing human contributions to accidents: The new view on error and performance. *Journal of Safety Research*, 33, 371–385.

Harris, R. J. 1975. *A primer of multivariate statistics.* NY: Academic Press.

Kerlinger, F. N. 1973. *Foundations of behavioral research* (2nd ed.). NY: Holt, Rinehart and Winston.

Klein, G., Rasmussen, L., Lin, M. H., Hoffman, R. R., and Cast, J. 2014. Influencing preferences for different types of causal explanation of complex events. *Human Factors*, 56, 1380–1400.

Miller, C. O. 2000. Resolving "action failure." The ISASI Forum (pp. 14–16), April–June.

National Transportation Safety Board. 2000a. *In-Flight Breakup over the Atlantic Ocean, Trans World Airlines Flight 800, Boeing 747-131, N93119, Near East Moriches, New York, July 17, 1996*. Report Number AAR-00-03. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2000b. *Highway Accident Report, Collision of Greyhound Lines, Inc. Motorcoach with Tractor Semi-Trailers on the Pennsylvania Turnpike, Burnt Cabins, Pennsylvania, June 20, 1998*. Report Number: HAR-00-01. Washington, DC: National Transportation Safety Board.

Packer Engineering. 2000. *Report Submitted to Special Commission on the 1999 Bonfire*. Naperville, IL: Packer Engineering.

Rasmussen, J., Pejtersen, A. M., and Goodstein, L. P. 1994. *Cognitive systems engineering*. NY: John Wiley & Sons.

Special Commission on the 1999 Texas A & M Bonfire. 2000. Final Report. College Station, TX: Texas A&M University.

Vaughan, D. 1996. *The Challenger launch decision: Risky technology, culture, and deviance at NASA*. Chicago, IL: The University of Chicago Press.

Vicente, K. J. 1997. Heeding the legacy of Meister, Brunswik, and Gibson: Toward a broader view of human factors research. *Human Factors*, 39, 323–328.

Section II

Antecedents

4

Equipment

> Designers go astray for several reasons. First, the reward structure of the design community tends to put aesthetics first. Design collections features prize-winning clocks that are unreadable, alarms that cannot easily be set, can openers that mystify. Second, designers are not typical users. They become so expert in using the object they have designed that they cannot believe that anyone else might have problems; only interaction and testing with actual users throughout the design process can forestall that. Third, designers must please their clients, and the clients may not be the users.
>
> **Norman, 1988**
> *The Design of Everyday Things*

Introduction

A well-known accident involving a complex system, the March 1979 accident at the Three Mile Island nuclear generating plant (Kemeny, 1979), demonstrated the extent to which poorly designed equipment can adversely affect operator performance. Investigators found that the operators, confused by the many alarms and warnings signaling a malfunction, had difficulty interpreting the displayed data to understand the event.

In World War II, the U.S. Army Air Corps and British Royal Air Force each recognized the importance of equipment design on the safety of pilots who were in training. Both changed aspects of cockpit features to enhance flight safety, based on their studies of pilot–aircraft interactions (Meister, 1999; Nickerson, 1999). Researchers have continued to study and apply human factors and ergonomics principles to the design of equipment in both simple and complex systems to improve system safety (e.g., Corlett and Clark, 1995; Karwowski and Marras, 1999; Wickens and Hollands, 2000).

Research has shown that, although operators obtain much of the operating system information they need from system displays, they use other sources as well. Mumaw, Roth, Vicente, and Burns (2000) found that operators actively acquire information from other operators, maintenance and

operating logs, and from their own observations of operating conditions. Today, it is recognized that experienced operators obtain system information from many sources, but still rely extensively on the equipment itself to understand the system state. This chapter will examine features of equipment design to understand their effects on operator performance.

Visual Information

Operators acquire and use system-related information to understand the current and near-term system states and the associated operating environment. Operators can obtain this information through any sensory modality. Although most systems present system information visually and aurally, some use tactile cues as well, such as the stick shaker in high performance aircraft that signals an impending aerodynamic stall. Presenting information through different sensory modalities has unique advantages and disadvantages in terms of their effects on operator performance.

Visual displays enable information with a high degree of precision to be presented. As a result, most system information is presented visually. But visually presented information must be displayed properly for operators to efficiently obtain critical information, and operators must be looking at the displays in order to access the information.

Visual displays differ in the ease with which operators obtain and interpret system-related information, depending on different facets of their presentations. These features affect the quality of operator interpretation of visual information,

- Number of displays
- Organization and layout
- Conspicuity
- Interpretability
- Trend portrayal

The Number of Displays

Visual information is presented primarily through either analog or digital displays. Analog displays are found in older systems, and generally show a one-to-one relationship between a component or subsystem and the corresponding display of information. Systems with numerous components and subsystems may have hundreds of analog displays, each providing critical information about one component or subsystem. For example, the illustration of a Soviet era nuclear power plant in Figure 4.1 shows a display with dials too numerous for operators to readily monitor. Should one show

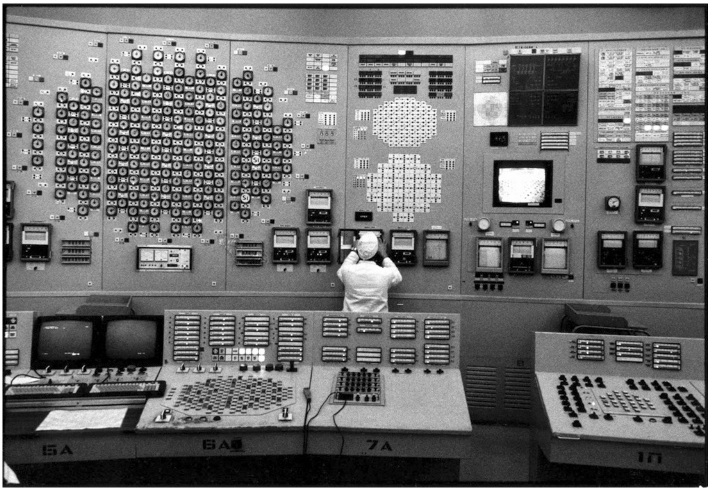

FIGURE 4.1
Soviet era nuclear power plant. Note the numerous dials and controls. (Copyright Gary Knight. Reprinted with permission.)

information revealing an unusual or unexpected occurrence, the operator would be unlikely to notice the information without additional assistance. The operator would have to search the displays to identify and locate the needed information before even trying to comprehend the cause of the occurrence. During high workload periods, such as during anomalous operating conditions, numerous displays could interfere with an operator's ability to quickly locate and understand the critical data in the available time.

Organization and Layout

Display organization can influence an operator's ability to access needed system data, especially in a system with numerous displays. Display groupings that do not conform to the logic that operators use to understand the system state can prolong the time they need to find and understand the needed data. The more readily the display organization allows operators access, the fewer the opportunities for operator error.

Rasmussen and Vicente (1989) propose organizing information according to what they term "ecological interface design," by matching the organization of the displays to the operator's mental model of the system state. This will support an operator's cognitive activities during interactions with the systems, and hopefully reduce opportunities for error.

Poorly organized displays, "cluttered" displays, or displays that do not separate critical information from noncritical information will adversely affect operator performance. Wickens and Carswell (1995) refer to these adverse effects as the "information access cost" of display organization. The greater

the cost, the more cognitive effort operators exert and the more time they will need to access and interpret critical information.

Conspicuity

The greater the contrast between a display feature and that of other displays, the more conspicuous the displayed data will be and hence, the lower the operator's information access cost. Conspicuity is influenced by display size, contrast, and luminance relative to adjacent displays. The larger a display, and the relatively brighter it is compared to others and its surroundings, the greater it will stand out against the prevailing background, and the more likely the operator will notice it (e.g., Sarter, 2000).

Interpretability

The more interpretable the data, the more readily operators can use the information to understand the system state. Consider a gauge that displays an automobile's coolant temperature. By itself, the temperature has little meaning to those who are unaware of the engine's optimum temperature range in "normal" operating conditions. But a gauge that displays a picture of an engine as a face that smiles, with the smile changing to a frown and the face color becoming a deeper red as the temperature increases would be considerably more interpretable to drivers who may otherwise not understand the relevance of the temperature to the engine status.

Designers have used different methods to increase operators' ability to understand visually presented data. Abbott (2000) describes a method of presenting aircraft engine information that is considerably more interpretable than current displays of the same information, because the presentation more closely matches the needs of the operator. Aircraft engine-related data displays, and their effects on operator performance, will also be discussed in Chapter 10.

Color can also readily convey information. Parsons, Seminara, and Wogalter (1999) found that in numerous countries and cultures, the color red indicates hazardous conditions. Similarly, green and yellow or amber signify normal and cautionary operating conditions, respectively. Designers have often placed colors behind a pointer or gauge on analog displays so that operators can quickly recognize the value of the component parameter as the pointer approaches the color. Automobile drivers use tachometer colors to determine when an engine "red lines" or approaches its maximum safe operating range to obtain maximum engine performance when changing gears.

Digital displays allow substantial flexibility in presenting data. They can be designed to present pictures, smiles, or frowns, for example, to convey information. Some systems use flow diagrams to display the state of electrical, pneumatic, and other subsystems, enabling operators to quickly identify a flow anomaly and recognize its impact on the system as a whole.

Although digital displays offer flexibility in presenting information, the relationship of display flexibility to operator performance has not been demonstrated consistently. Miller and Penningroth (1997) conclude that digital displays may not necessarily result in superior operator performance relative to analog displays. By contrast, Abbott (2000) believes that properly designed digital displays can enhance operators' ability to interpret data.

Trend Portrayal

Because of the dynamism of many complex systems, operators need to quickly detect and interpret the direction and rate in which component parameters change, in order to understand their effects on system state. Nonetheless, understanding the state of the system at any one given moment, depending on the system, may not be as critical as recognizing how quickly a system state is changing and the direction of its change. Analog displays have traditionally presented direction information by the clockwise or counterclockwise movement of an indicator or pointer, and rate of change by the rapidity of that movement. These features are often seen in airplane disaster movies, for example, in which the rapidly unwinding altimeter—the instrument that depicts an aircraft's altitude—conveys the seriousness of the situation. Some analog displays use vertical or horizontal "tapes" or lines to convey trend information. The lines move up or down or left or right to convey the direction and rapidity of system changes.

Digital displays do not necessarily present trend information better than do analog displays. A digital format that presents system parameters in Arabic numerals gives the operator precise parameter information. However, in the event of a rapid change, the numerals corresponding to the parameter would also change rapidly, and operators may not be able to quickly interpret the direction of change, that is, whether the parameters are increasing or decreasing. Yet, properly designed digital displays can present trend information in at least a comparable, if not superior way, to analog displays. These generally depict the nature and rate of the change pictorially to minimize operators' time spent interpreting trend data, as in the illustration of the face to portray engine coolant temperature.

Aural Information

Visually presented information has one major drawback; operators must look at the information to receive it. If they are looking at displays of noncritical information, or engaged in other tasks and focusing elsewhere, they will not receive the information. Designers compensate for this shortcoming by adding aurally presented information to the presented information.

Because of the salience of aurally presented information—even inattentive operators receive the information—designers have usually relied on aurally presented information to rapidly communicate critical information to operators (e.g., Patterson, 1990; Edworth, Loxley, and Dennis, 1991). However, aurally presented information also has limitations in that the conveyed information is less precise than visually presented information, and it can quickly distract operators and hinder their performance (e.g., Banbury, Macken, Tremblay, and Jones, 2001).

The quality of aurally presented information is primarily influenced by a number of factors,

- Conspicuity
- Distractibility
- Uniqueness
- Accuracy
- Relative importance

Conspicuity

To perceive aurally presented information operators must distinguish the critical sound from other sounds. Designers generally use of one of two methods to increase the conspicuity of critical sounds relative to those of other sounds, increasing volume or varying such sound elements as pitch, frequency, and rhythm. Patterson (1990) suggests increasing the volume of critical sounds by at least 15 dB over the volume of background noises to make them clearly audible. In environments in which the ambient sounds are fairly loud, this could make the aurally presented information quite loud, even approaching dangerous levels over extended periods.

Distractibility

Once aural information has been presented, continuing to present the sounds adds little additional information, and can distract operators and degrade their performance. The longer aural information continues to be presented and the more conspicuous the sound, the more likely the information will interfere with and degrade operator performance. On the other hand, Banbury et al. (2001) point out that after about 20 minutes of exposure the distracting effects of sounds are reduced. Unfortunately, exposure to interfering sounds for as long as 20 minutes can substantially degrade operators' ability to respond effectively in that interval.

Aurally presented information should cease to be presented after operators have received and understood it. However, many systems cannot recognize when this has been accomplished. Too often, aural information first informs and then distracts operators.

Aural information can also distract and interfere with the work of operators who were not targets of the initial information, especially in small operating environments such as locomotive cabs, ship bridges, or aircraft cockpits. Allowing operators to silence alerts might negate these disadvantages. However, as will be discussed shortly, systems that allow operators to silence alerts have other disadvantages.

Accuracy

Aurally presented information that is inaccurate or inconsistently useful will lose its value overtime, eventually failing to elicit operator attention. Yet, designers generally consider the consequences of missed alerts, where aural information is presented but operators do not respond, to be more critical to system safety than those of false alarms, where alerts are sounded but a response is unnecessary. As a result, designers tend to favor providing more rather than fewer alarms in a system to ensure that operators are informed of potentially important systems-related information.

Further, designers set the threshold in these systems sufficiently low to ensure that critical events will elicit alerts, even if this results in noncritical events eliciting alerts as well. Unfortunately, doing so with sufficient frequency can expose operators to repeated false alarms, which has been found to reduce operator sensitivity to the alerts, and as Sorkin (1988) found, on occasion can even lead to outright operator silencing them altogether.

In a January 1987 rail accident near Baltimore, Maryland, the locomotive engineer and brakeman, who were operating two freight locomotives, silenced an alarm they had considered distracting, a shrill whistle that sounded when the head locomotive passed a stop signal (National Transportation Safety Board, 1988). Neither operator noticed or responded to the stop signal, and the train consequently entered a track section that was reserved for an approaching, high-speed, passenger train. The passenger train then struck the freight locomotives, killing its engineer and 16 passengers. Investigators concluded that the aural alert would have informed the freight locomotive engineer and brakeman of their impending entry onto a prohibited track section. Investigators also found that the two operators had smoked marijuana before the accident and were impaired at the time.

Uniqueness

Designers create distinct sounds that are associated with different system elements, system states, or desired operator responses. Uniqueness characterizes the degree to which a sound is associated with specific system-related information. Operators learn to associate certain sounds with their corresponding system states so that when the sounds are heard the operators can quickly recognize their meaning, and will be unlikely to confuse the sounds with others. For example, emergency vehicles use distinctive sirens to alert

drivers in order to increase the likelihood that drivers will quickly recognize and respond to them.

Aurally presented information can take a variety of forms. "Traditional" sounds such as bells, whistles, horns, and sirens are found on older equipment. Each sound can be readily distinguished from others and, if loud enough, could be heard over ambient sounds.

As with visually presented information, modern digital equipment usually offers more flexibility in presenting aural information than does older equipment. Synthesized or recorded human voices that articulate simple voice messages can be used, in addition to traditional sounds (Stern, Mullennix, Dyson, and Wilson, 1999). Belz, Robinson, and Casali (1999) proposed using auditory icons, such as screeching tires, sounds that can be distinctly associated with particular system states, to enhance operator recognition and response to the sounds.

Today, digital capabilities have expanded to the point that many automobiles are equipped with navigation capabilities that can guide drivers to their destinations, taking traffic flow into account as well as proximity to other vehicles, whether they are in front, behind, and alongside. Drivers, if using vehicles not so equipped, can use their smartphones to provide navigation and other capabilities, with the ability as well to select from a number of voices, male and female, for example, with different accents or different languages to direct them, so that the simple instructions, for example, "turn left in 70 meters," can be quickly understood. As will also be discussed in Chapter 10, vehicles equipped with electronic devices, can, if needed, provide accident investigators with useful information not only about selected routes, but also about braking, lane changing, and other data that can describe driver performance before an accident.

Relative Importance

A single event can precipitate multiple system warnings or alerts, each reflecting the state of a single system parameter rather than the event that led to the parameter state. In some systems, certain phenomena can elicit so many sounds and alarms from the effects of an event, rather than the precipitating event itself, that a cacophony of sounds is produced. When this occurs, the operator's ability to effectively evaluate the individual alerts in order to understand the phenomenon that led to the alerts, rather than the effects of the phenomenon on the system, is made considerably more difficult.

Some systems inhibit both visual and aural alerts, without operator action, during critical operating cycles. This reduces the likelihood that noncritical alerts would distract operators during critical tasks, as occurred in the crash of a Boeing 757 off the coast of Lima, Peru, in October 1996. Investigators found that pitot-static tubes, critical components that are necessary to measure airspeed, climb and descent speeds, and altitude, were blocked by a maintenance error, which led to the speed and altitude displays presenting

erroneous information to the pilots (Accident Investigation Commission, 1996). After takeoff, numerous airspeed and altitude warnings and alerts, including low terrain, low airspeed, impending stall (the "stick shaker"), and wind shear, sounded. The alerts began within 5 seconds of each other and continued until impact. Each signaled a specific hazardous situation, but there was no alert that corresponded to the failure that had caused the multiple alerts—the blocked, and hence inoperative pitot-static system. The pilots were unable to determine the cause of the alerts. More important, operating at night and over water they could not visually estimate the airplane's airspeed and altitude. The alerts distracted the pilots, hindered their communications, and interfered with their ability to effectively diagnose the anomaly.

Multiple warnings or alerts that sound simultaneously or in quick succession often require the highest level of operator performance. Yet, they are often presented when operator workload tends to already be high because operators must, (1) continue to operate the system, (2) diagnose and respond to the anomaly, and (3) avoid causing additional damage. These tasks are challenging in combination, but when multiple alerts sound simultaneously during periods of high workload they can degrade performance.

Some years later, an accident occurred that shared many of the characteristics of the 1996 Boeing 757 accident, an Airbus A-330 crashed into the Atlantic after the pitot tubes became blocked. Investigators attributed the blocked pitot-static tubes to ice crystals that formed after the airplane entered an area of adverse weather while the flight was at cruise altitude (Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile, 2012). The initial aural alert that the crew received pertained to the autopilot's disengagement, not to the blocked pitot tubes. This alert, which serves to inform the crew that manual airplane control is needed, is critical to ensure that pilots recognize that the autopilot is no longer operating, valuable information to help pilots recognize that they must address the alert and manually control the airplane. However, the underlying cause of the disengagement, the rapid alteration in measured airplane speed caused by the pitot-tube blockage, was not presented. As a result, investigators noted that,

> Since the salience of the speed anomaly was very low compared to that of the autopilot disconnection, the crew detected a problem with this disconnection, and not with the airspeed indications. The crew reacted with the normal, learned reflex action, which was to take over manual control … (Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'AviationCivile, 2012, p. 173)

The pilots' failure to recognize that the airspeed they were perceiving was inaccurate led to their failure to recognize the cause of the problem that they encountered and their subsequent mismanaging of airplane control. The airplane stalled and crashed into the ocean 4 minutes and 23 seconds later, killing all 228 passengers and crew onboard.

Kinesthetic/Tactile Alerts

Some have proposed presenting information through sensory modalities other than visual and aural ones to compensate for the limitations of presenting information in these modalities (e.g., Sklar and Sarter, 1999; Sarter, 2000). Transport airplane designers use both kinesthetic and aural cues to simultaneously alert pilots to a critical event, an aerodynamic stall. A stall requires immediate pilot action or the airplane may crash. Just before reaching the airspeed that would precede an aerodynamic stall, pilots hear a particular alert and feel a distinctive control column motion, sensations that are very difficult to ignore. However, as with aurally presented information, constant presentation of kinesthetically or tactually presented information can distract operators and degrade their performance.

Controls

Operators use controls to modify system state and system operation. Control design characteristics can influence operator performance and the likelihood of error, as can displays. Controls can take many shapes and forms, move in a number of directions, and be placed in a variety of locations. Automobiles, for example, employ at least three primary controls to enable drivers to direct their vehicles. The accelerator controls forward motion, the brake pedal slows or stops the vehicle, and the steering wheel controls lateral motion. Vehicles equipped with standard transmissions have two additional controls, a clutch and gearshift lever, for changing transmission gears as vehicle speed and engine rotation rates change. Other controls enable drivers to maintain selected speeds, and control windshield wiper speed and headlight brightness, sound the horn, and engage turn signals, for example. Further controls allow passengers and drivers to change window height, audio and video system characteristics, and vehicle interior temperature or ventilation levels.

Investigators generally apply these criteria to assess the quality of control design,

- Accessibility and location
- Direction of movement and function
- Shape
- Placement
- Standardization

The quality of keyboard and touchscreen and other digital type controls, which are increasingly used in complex systems, is evaluated according to other criteria that will be addressed subsequently in this chapter.

Accessibility and Location

Accessibility, the ease with which operators can reach and manipulate desired controls, can influence the quality of operator performance. In systems with relatively unlimited space, in which time to manipulate controls is not critical, accessibility will not substantially influence operator performance. However, in systems with space limitations, designers need to shape and locate controls so that operators can readily access them, irrespective of the operators' physical characteristics such as arm length. Well-designed systems have controls that operators can reach and manipulate without moving far from their stations.

Inaccessible, hidden, or obscured controls can delay operator response when time is critical and thus serve as antecedents to error. Large church or concert organs illustrate well-designed controls. Organists adjust their access to the controls by moving their seats, and use both their hands and feet to operate the controls, the keys, and the pedals.

Direction of Movement and Function

The direction in which a control moves should intuitively correspond to the direction of change in the corresponding component. Raising a control should increase an aspect of the system such as production rate, component height, or illumination level, while lowering a control should reduce it. Depressing a button should engage a component function while releasing the depressed button should disengage it. Controls that move in directions that are counterintuitive can become antecedents to error if operators actuate the control incorrectly after using similar controls that move in a "standard" direction.

Mode Errors

Systems with limited available space, as well as advanced electronic controls, often employ multifunction controls in which one device controls multiple system functions. Operators who are unfamiliar with or do not perceive the distinction among the various control functions may initiate a control action and an unanticipated system response, what has become known as a mode error (Norman, 1988).

Multifunction controls can be designed to reduce opportunities for mode errors by giving operators unambiguous information or feedback regarding the system's operating mode. The quality of the feedback is affected by

the same visual, aural, and kinesthetic factors discussed previously. Visually presented feedback should be sufficiently conspicuous to enable operators to receive the information. Aurally presented information is likely to be the least confusing, but operators will tend to ignore aural information if presented repeatedly.

Investigators concluded that the pilots of an Airbus A-320 that crashed short of the runway at Mont St. Odile, France, in 1992, committed a mode error while preparing to land (Commission of Investigation, 1993). A single control, a knob that turned clockwise or counterclockwise to increase or decrease the rate of change in the desired mode, also controlled both the airplane's descent rate and its flight path angle. Pilots selected the mode by either depressing or pulling the knob and then turning it to establish the desired descent rate or descent angle. Incorrectly controlling the knob engaged the mode other than the one intended.

Investigators concluded that the pilots had inadvertently selected the wrong mode, and established a descent rate that was triple the typical rate, believing that they had commanded a moderate descent angle. Because of the dual purpose of the control knob, and ambiguity in the information presented regarding the descent rate that they had engaged, the pilots were not aware of their error and then failed to notice the rapid descent to the ground.

Shape

Controls can take a number of forms, designs, and shapes, such as knobs, buttons, wheels, switches, levers, or pedals. Designers may shape a control to resemble a distinctive task or function. In some systems, regulators have mandated specific design characteristics. For example, the lever that extends or retracts airplane landing gear is required to be circular to reduce the possibility of confusion with an adjacent control. By shaping the lever to correspond to the shape of the controlled component, the aircraft wheels, pilots can recognize the control by touch alone, minimizing the possibility of control confusion.

Control shape can play an important role in operator performance. In high workload or stressful situations, operators may not have the time to visually identify a control before manipulating it. Rather, they may locate and select controls by touch alone, without visual verification. In these circumstances, operators may find similarly shaped controls to be undistinguishable, and select the wrong control.

Placement

Controls that actuate different subsystems or have different functions (e.g., go fast and go slow), should not be placed near each other, and if so, should be shaped differently so that in the event that operators must engage them

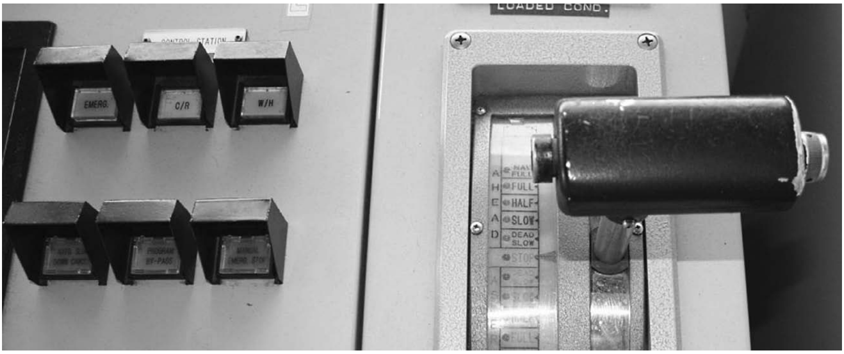

FIGURE 4.2
Identically shaped controls in which one rapidly speeds up and the other slows down the vessel's engine, placed adjacent to each other, on the first row, center (speed up) and rightmost (slow down) positions. In both cases, actuation resulted from depressing the buttons. (Courtesy of the National Transportation Safety Board.)

quickly, they can identify them without having to visually verify that they have actuated the desired control to initiate the control operation desired. The effects of placing identically designed controls, with differing actuation results, adjacent to each other can be seen in the investigation of a marine accident (National Transportation Safety Board, 2011).

In this accident, which was caused by a marine pilot's late recognition of the need for a turn (influenced by his fatigue), the vessel he was piloting first collided into a vessel traveling in the opposite direction as his vessel, and then collided with a second, docked vessel. Just before the accident, the captain, seeing the impending collision, attempted to rapidly slow the vessel by actuating a control, a button that caused the engine to quickly slow. However, the button actuating that control was located adjacent to an identical button that caused the engine to do the opposite of what the captain intended, speed up rapidly, the button that the captain actually depressed. Although investigators determined that at the time the captain actuated the control the accident could not be avoided, investigators faulted a design that was counter to the standards of good design (Figure 4.2).

Standardization

Operators have come to expect a certain configuration, shape, and direction of movement in the controls that they manipulate. Unfortunately, unless regulators establish rules governing the design of both displays and controls, designers may create designs that suit their own rather than the operators' needs. This can lead to differences in the shape of similar controls on comparable equipment. Those who have driven cars at night that are different from their own, and had difficulty locating and engaging the windshield wipers

or headlights because the controls were located in unexpected places, have witnessed the errors these control differences can create.

So long as operators interact with only one type of equipment, nonstandard control shapes, locations, and directions of movement will not create antecedents to errors. However, operators interacting with comparable equipment that have different controls and displays could, out of habit, move a control incorrectly or direct the wrong control when alternating between equipment types. If operators repeatedly reach one location to access a control, or move it in a certain direction to accomplish an action, they will likely continue these movements on different equipment, even if the movements produce unintended consequences.

Some years ago, the National Transportation Safety Board found that the rate at which pilots failed to extend the landing gear before landing was higher among pilots of aircraft that had been designed and built by one manufacturer than with pilots of comparable aircraft of other manufacturers (National Transportation Safety Board, 1980). The NTSB attributed this difference to the location of the landing gear and flap controls. Controls in the cockpits of the airplanes with the higher gear up accident rates were located in different locations than were controls on most other aircraft. Investigators concluded that pilots who had operated other aircraft would inadvertently reach for and select the "wrong" controls occasionally, actions that would have been appropriate on those aircraft.

Unfortunately, there is no short-term solution for a lack of standardized controls and displays. Designers could reduce the role of this antecedent to error by adhering to a common control and display design standard. However, a transition period would be needed to implement a standard to prevent operators from being confused by what may be a new design. Equipment already in service will likely continue to remain in service until it is no longer economically feasible to do so. In order to standardize comparable controls and displays, the time needed to introduce new or redesigned equipment into complex systems and to train operators to use the new designs may be considerable. Unless regulators require standardizing the controls and displays in the systems they oversee, standardization will be unlikely.

Keyboard Controls

In older systems, operators often needed to exert considerable physical force to manipulate controls. Today, however, systems use keyboard controls, either with the familiar QWERTY format derived from the typewriter keyboard, a variant, or graphic interfaces on screens to actuate system controls. Operators using keyboard controls are physically able to control the system without error, so long as they don't inadvertently strike the wrong key. Without effective feedback from the system, operators may incorrectly

believe that they have actuated the correct keyboard controls even if they have not. Highly automated systems largely rely on keyboards with well-separated keys that minimize slips when operators manipulate them by touch alone, and place the keyboards in a location that minimizes fatigue over extended use.

In addition, in contemporary systems graphic user interfaces and touch screens have increasingly been implemented as system controls. These are less likely to lead to inadvertent operator errors than are keyboards, as operators must visually determine the selections they make through a display on the screen. Other characteristics of automated systems and their effects on operator performance are discussed in more detail in Chapter 15.

Summary

The manner of presenting system-related information to operators can affect their understanding of the system state. Information that involves a high degree of precision is generally presented visually. The number of displays, their conspicuity, organization, and portrayal of trends in system performance influences operators' ability to obtain and interpret system information. Information that is difficult to access and interpret can lead to misinterpretations and errors.

Information that requires immediate attention, independent of operators' focus, is generally presented aurally. Volume, precision, and conspicuity influence how well operators receive and comprehend the information. Continued presentation of aural information can distract and interfere with an operator's ability to concentrate, perform other tasks, and perceive other aurally presented information. Sounds should be distinctive and associated with system states or required operator actions to continue to be meaningful. Sounds that are inconsistently associated with system information or operator response will lose their meaning over time.

The design of controls that operators use to alter or modify system operations can affect their performance. Controls should be readily accessible and move in the direction that corresponds to the direction of change in the associated system parameter. Control shapes should be readily distinguishable from one another, particularly if adjacent. Controls with different functions should be shaped differently, and placed away from each other to reduce the likelihood of operators inadvertently actuating the wrong controls. Over the long term, standardization of control and display features will reduce the potential for confusion and errors among operators who work on comparable, but nonstandardized equipment.

DOCUMENTING EQUIPMENT

- Photograph, video record, or otherwise capture a record of displays and controls in the operating environment of the equipment involved in the event. If this is not possible, refer to equipment handbooks for operating station diagrams, as necessary.
- Use comparable systems or a system simulator, noting differences between the two, if the equipment was excessively damaged as a result of the event.
- Interview designers to obtain information about the philosophy that guided the display and control design.
- Interview designers, instructors, and operators, and refer to operating manuals, to obtain information on differences between designers' and instructors' intentions and operator practices.
- Refer to ergonomics handbooks for guidance, if necessary, when evaluating display or control design features (e.g., Sanders and McCormick, 1993; Ivergard, 1999).

DISPLAYS

- Document the number of displays and their locations, and note the displays that operators use to understand the event, compared to the total number of displays presented nearby.
- Note how closely the logic of the organization corresponds to the way operators access displays or their associated controls.
- Contrast the color, brightness, and data size in the display to comparable features in adjacent displays to determine display conspicuity.
- Identify display colors, pictures, diagrams, design, or other features that affect data interpretability and if necessary, refer to operating manuals and handbooks to understand the meaning and relevance of the displayed data.
- Determine the portrayal of direction and rate of changes in parameter trend information.

AURALLY PRESENTED INFORMATION

- Measure sound volume, duration after initial presentation, volume of ambient sounds, and changes in features of the sounds of interest with changes in component status.
- Document features of aurally presented information among sound elements such as volume, pitch, frequency, and rhythm.

- Determine the meaning of each aural warning, alert, or other sound, and its association with specific system states.
- Identify sounds that call for a specific action or response, the information they convey, and the corresponding required or advised operator action or response.
- Measure the length of time alerts sound before they are silenced, either by the equipment or by the operators.
- Document operator actions needed to silence alerts, the system state that will resume the alert, and the length of time needed from the first sounding of the alert to its operator-initiated silencing.
- Interview operators to determine the actions they have taken to silence the alerts.

CONTROLS

- Document the location and positions of system controls, their accessibility to operators, and obstructions to accessibility.
- Determine the direction of movement of the controls and their correspondence to the direction of change in component parameters.
- Determine the feedback operators receive concerning changes in system state.
- Assess shapes, sizes, and distances among controls.
- Determine differences among control parameters among comparable systems if operators interact with equipment of different manufacturers.
- Document the accessibility, sizes, and distances among keyboard controls.

References

Abbott, T. S. 2000. Task-oriented display design: The case of an engine-monitoring display. In N. B. Sarter and R. Amalberti (Eds.), *Cognitive engineering in the aviation domain* (pp. 133–152). Mahwah, NJ: Erlbaum.

Accident Investigation Commission. 1996. *Informefinale, accidentede la Aeronave Boeing 757-200, operadapor la empresa de transporteAereo Del Peru S. A., Aeroperu, ocurrido el dia02 de Octubre de 1996*. Final Report, accident of the Boeing 757-200, operated by the transport company AeroPeru, October 2, 1996. Lima, Peru: Accident Investigation Commission.

Banbury, S. P., Macken, W. J., Tremblay, S., and Jones, D. M. 2001. Auditory distraction and short-term memory: Phenomena and practical implications. *Human Factors*, 43, 12–29.

Belz, S. M., Robinson, G. S., and Casali, J. G. 1999. A new class of auditory warning signals for complex systems: Auditory icons. *Human Factors*, 41, 608–618.

Bureau d'Enquêtes et d'Analyses Pour la Sécurité de l'AviationCivile. 2012. *Final Report on the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro—Paris*. Paris: Bureau d'Enquêtes et d'Analyses Pour la Sécurité de l'AviationCivile.

Commission of Investigation into the accident on 20 January 1992 of Airbus A320 F-GGED near Mont Sainte-Odile. 1993. *Official Report into the Accident on 20 January 1992 Near Mont Sainte-Odile (Bas-Rhin) of the Airbus A320 registered F-GGED, operated by Air Inter.* Paris: Commission of Investigation into the accident on 20 January 1992 of Airbus A320 F-GGED near Mont Sainte-Odile.

Corlett, E. N. and Clark, T. S. 1995. *The ergonomics of workspaces and machines* (2nd ed.). London: Taylor & Francis.

Edworth, J., Loxley, S., and Dennis, I. 1991. Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors*, 33, 205–231.

Ivergard, T. 1999. Design of information devices and control. In W. Karwowski, and W. S. Marras (Eds.), *The occupational ergonomics handbook* (pp. 97–138). Boca Raton, FL: CRC Press.

Karwowski, W. and Marras, W. S. 1999. *The occupational ergonomics handbook*. Boca Raton, FL: CRC Press.

Kemeny, J. G. 1979. *The Need for Change: The Legacy of TMI*. Report of the President's Commission on the Accident at Three Mile Island. Washington, DC: Government Printing Office.

Meister, D. 1999. *The history of human factors and ergonomics*. Mahwah, NJ: Erlbaum.

Miller, R. J. and Penningroth, S. 1997. The effects of response format and other variables on comparisons of digital and dial displays. *Human Factors*, 39, 417–424.

Mumaw, R. J., Roth, E. M., Vicente, K. J., and Burns, C. M. 2000. There is more to monitoring a nuclear power plant than meets the eye. *Human Factors*, 42, 36–55.

National Transportation Safety Board. 1980. *Special Investigation Report, Design Induced Landing Gear Retraction Accidents in Beechcraft Baron, Bonanza, and Other Light Aircraft*. Report Number: SR-80-01. Washington, DC.

National Transportation Safety Board. 1988. *Railroad Accident Report, Rear-End Collision of Amtrak Passenger Train 94, The Colonial, and Consolidated Rail Corporation Freight Train ENS-121, on the Northeast Corridor, Chase, Maryland, January 4, 1987*. Report Number: RAR-88-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2011. *Marine Accident Report, Collision of Tankship Eagle Otome with Cargo Vessel Gull Arrow and Subsequent Collision with the Dixie Vengeance Tow, Sabine-Neches Canal, Port Arthur, Texas*. Report Number MAR-11-04. Washington, DC: National Transportation Safety Board.

Nickerson, R. S. 1999. Engineering psychology and ergonomics. In P. A. Hancock (Ed.), *Human performance and ergonomics* (pp. 1–45). San Diego, CA: Academic Press.

Norman, D. A. 1988. *The psychology of everyday things*. NY: Basic Books.

Parsons, S. O., Seminara, J. L., and Wogalter, M. S. 1999. A summary of warnings research. *Ergonomics in Design*, January, 21–31.

Patterson, R. D. 1990. Auditory warning sounds in the work environment. *Philosophical Transactions of the Royal Society of London*, 327, 485–492.

Rasmussen, J. and Vicente, K. J. 1989. Coping with human errors through system design: Implications for ecological interface design. *International Journal of Man-Machine Studies*, 31, 517–534.

Sanders, M. S. and McCormick, E. J. 1993. *Human factors in engineering and design* (7th ed.). NY: McGraw-Hill.

Sarter, N. B. 2000. The need for multisensory interfaces in support of effective attention allocation in highly dynamic event-driven domains: The case of cockpit automation. *International Journal of Aviation Psychology*, 10, 231–245.

Sklar, A. E. and Sarter, N. B. 1999. Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event driven domains. *Human Factors*, 41, 543–552.

Sorkin, R. D. 1988. Why are people turning off our alarms? *Journal of the Acoustical Society of America*, 84, 1107–1108.

Stern, S. E., Mullennix, J. W., Dyson, C., and Wilson, S. J. 1999. The persuasiveness of synthetic speech versus human speech. *Human Factors*, 41, 588–595.

Wickens, C. D. and Carswell, C. M. 1995. The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors*, 37, 473–494.

Wickens, C. D. and Hollands, J. G. 2000. *Engineering psychology and human performance*. Upper Saddle River, NJ: Prentice-Hall.

5

The Operator

> Each person—the butcher, the parent, the child—occupies a different position in the world, which leads to a unique set of experiences, assumptions, and expectations about the situations and objects she or he encounters. Everything is perceived, chosen, or rejected on the basis of this framework.
>
> **Vaughan, 1996**
> *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*

Introduction

Our uniqueness as individuals—the way we were raised and educated, our work experiences, and genetic makeup, affect the way we perceive the world and act upon it. Because of these differences two operators, encountering identical system states, could perceive them differently, even if they have had identical training and similar backgrounds.

In the past, investigations of error largely focused on the operator, often to the exclusion of other system elements that may have contributed as much, if not more, to operator errors than factors related to the operator who had committed the errors. For example, checklists that were developed to guide investigations of error, many of which are still widely used today, focus primarily on characteristics of the operator rather than other system elements (e.g., International Civil Aviation Organization, 1993).

The role of the operator has changed over the years, as technology has advanced and been increasingly implemented into complex systems. With this change, the role of the operator has changed as well as he or she increasingly interacts with the system through technology. This has also changed the type of errors operators commit from action errors to more cognitive ones (Coury et al., 2010). The approach to investigating error advocated in this text considers operator-related factors within a broad view of error. It does not minimize the influence of operator factors in incident and accident causation; these can, and do, affect performance and lead to error. Rather, it puts the error in the context of the system in which he or she operates,

with consideration of antecedents that are associated with both action and cognitive errors.

The central role of the operator in complex systems operations requires investigators to recognize the role of operator factors in system performance, factors that are associated with both action and cognitive type errors. This chapter will focus on operator-related antecedents to explain the effects of these factors on operator performance.

Physiological Factors

Operator-related antecedents can be categorized into one of two general classes: physiological or behavioral. Each includes antecedents with which most of us are familiar, having likely observed their effects in our own experiences, and each can affect operator performance over both the short and long term.

Physiological antecedents can temporarily or permanently degrade operator performance by impairing the operator or otherwise degrading his performance. The number of potential physiological antecedents that can influence operator error is sizeable, and numerous medical and physiological texts, journals, and articles have examined them. The major ways that physiological antecedents can degrade operator performance and lead to error will be reviewed, and data needed to determine if a relationship between the two exists suggested, but a full discussion of these antecedents is beyond the scope of this text.

General Impairment

Illness

Because operators must interpret data, recognize situations, anticipate system performance, and make decisions to effectively oversee system operations, any condition that degrades their cognitive skills could serve as an antecedent to error. Physiological antecedents can increase reaction times, interfere with cognition, and limit recall ability, among other impairing effects.

An operator is impaired when the quality of his or her performance has been degraded to a level below that needed to function effectively and safely. Operators are expected to notify their superiors when they are unfit for duty so that others can be found to serve in their place. However, many do not recognize the subtle effects of degrading factors on their performance and will report to work when they are ill or otherwise unfit for duty. They remove themselves from system operations only when their illness or discomfort is self-evidently impairing, without realizing the adverse effects of subtle impairment from the illness on their performance and on safety.

Researchers have found that even mild illness and discomfort, well below what many consider impairing, may still degrade performance and create antecedents to error. Smith (1990) examined the effects of two fairly minor illnesses, colds and influenza, on performance, ailments that account for what he termed a substantial proportion of all consultations in general medical practice. He measured cognitive skills and reaction times of volunteers who had been infected with a cold or influenza virus, and compared them with those who had been given a placebo. Those who were infected demonstrated significantly poorer cognitive performance and reaction times than those who were not infected, and many of those demonstrating degraded performance were in the incubation periods of their illnesses and thus, asymptomatic.

Medications

The potential effects of both prescribed and over-the-counter medications on operators vary according to the potency of the drug, the amount taken, the time since taking the drug, the rate at which the drug is metabolized, the presence of other drugs in the operators' systems, and individual variation in response to the drugs in question. The side effects of many drugs in and of themselves may adversely affect performance. For example, sedating antihistamines, found in many over-the-counter cold and allergy medications, slow reaction time and cause drowsiness. Their effects on operator performance can last hours after being consumed. Weiler et al. (2000) found that the performance of automobile drivers in a driving simulator was as adversely affected by an antihistamine, diphenhydramine, found in over-the-counter cold medications, as it was by alcohol.

In 1998, a commercial bus ran off of the road and struck a parked truck, after the bus driver had fallen asleep, killing him and six of the passengers (National Transportation Safety Board, 2000a). Toxicological analysis of specimens from the body of the driver revealed the presence of diphenhydramine and two other drugs, all contained in an over-the-counter preparation marketed for the treatment of colds and allergies. The amount of the drugs and their rates of metabolism indicated that the driver had likely taken the medication several hours before the accident. Investigators concluded that the drug exacerbated effects of two additional antecedents, an irregular sleep-work cycle, and the time of day, to cause the driver to fall asleep while driving.

In a retrospective study, the National Transportation Safety Board examined fatal accidents in a variety of transportation modes in the United States (National Transportation Safety Board, 2000b). Prescription medications were found in the bodies of over 21% of the general aviation pilots killed in aircraft accidents in 1 year, and in many of the bodies of operators killed in accidents in other transportation modes as well. Investigators concluded that both prescription and over-the-counter medications had impaired the operators and led to the accidents.

Operators whose performance was adversely affected by prescribed medications may have ingested multiple medications. In that case, there may be difficulty determining whether the effects of the medications were additive, where the effects of each medication added to those of the other medications taken, or interactive, where the influence of the medications on performance may have differed from more typical side effects because of the influence of the other medications in the person's system. While many prescribed medications, such as blood pressure drugs, have little effect on cognitive performance, others, particularly opiate pain drugs and antianxiety medications, known as benzodiazepines (e.g., Xanax, Prozac), have been demonstrated to adversely affect cognitive performance (e.g., Allen et al., 2003; Zacny, 2003). Potentially adverse effects of drugs on performance can be found in such references as the Physicians' Desk Reference, Internet information that manufacturers have made available, or published research.

Many over-the-counter medications carry generalized warnings on their labels about the hazards of driving or operating heavy machinery after use, but these warnings are often written in small font, and many users neither read the warnings nor recognize the need to apply them to their own situations. The extensive promotion of these drugs, their widespread availability and use, and the frequent lack of awareness of their side effects, increase the likelihood that operators will use them without recognizing their potential to impair and degrade performance. Prescription medications, which are required to have adverse effects listed and provided to patients, also may have their side effects ignored by users. Further, when the medications are dispensed, the physicians prescribing the medications and the pharmacists dispensing them may not inform users of potential adverse effects. Often people need to determine medication effects on their own, either by reading the information provided by the pharmacy or through internet sources. Many may be unaware of the effects on performance of the medications they are taking. This may be an issue in the performance of operators in industries where few operators are aware of medication side effects or the need to attend to them, or in industries in which use of medications may be prohibited, and hence their use can lead to job loss. In those instances, operators may keep their medication use, and/or medical condition hidden from their employers. Investigators should also recognize that medication use, whether prescribed or over the counter, may indicate an underlying medical condition that itself could be impairing. In those instances, medical records from the prescribing physicians are likely to be helpful to explain the nature of the condition that led to the medication use.

Alcohol and Drugs of Abuse

The effects of few, if any drugs, have been studied as much as those of alcohol. Even small amounts of alcohol can impair performance in a variety of cognitive and motor tasks (e.g., Ross and Mundt, 1988; McFadden, 1997).

A direct relationship has been established between the amount of alcohol in the bloodstream, measured by blood alcohol content or BAC, and the extent of impairment. The higher the BAC, the more impaired the person. In most of the United States, 8% BAC is considered impairing for automobile drivers, but lower levels, typically 5% BAC is considered impairing by medical researchers. Unusually high BAC concentrations, say 20% BAC or higher in an individual who is still able to function at some level, may indicate alcohol-dependency or addiction.

Those addicted to alcohol or other substances may experience withdrawal after a period of abstinence of even a few hours, withdrawal that can also impair performance (Tiffany, 1999). For example, cocaine, a highly addictive drug (National Institute on Drug Abuse, 1999), is a stimulant. After its effects have worn off cocaine users will likely be fatigued, particularly if they had taken the drug at a time when they would ordinarily have been asleep. Because fatigue impairs cognitive performance, the effects of withdrawal from sustained use of cocaine—effects that include mood alteration in addition to sleep disruption—can create antecedents to error.

Investigators determined that the pilot of a regional aircraft that crashed on approach to Durango, Colorado, had been fatigued after ingesting cocaine the night before the accident (National Transportation Safety Board, 1989). He and the first officer were flying a challenging approach through the Rocky Mountains and were about to land when they struck the ground several miles from the runway. Postmortem toxicological analysis of specimens from the captain's body found benzoylecgonine, cocaine's principle metabolite. Given the amount of the drug and its metabolite that were found, and the rate of cocaine metabolism, investigators determined that he had consumed the drug between 12 and 18 hours before the accident. Because the accident occurred at 6:20 p.m. local time, he would likely have consumed the cocaine the night before, at a time when he would ordinarily have been asleep, thus disrupting his normal sleep pattern. Further, after taking the cocaine, he would have had been expected to have encountered difficulty sleeping until the effects of the drug had worn off.

Investigators concluded that the captain's piloting skills "were likely degraded from his use of the drug before the accident" and that he was likely experiencing the effects of withdrawal, including, "significant mood alteration and degradation, craving for the drug, and post-cocaine-induced fatigue" (p. 29). The findings demonstrate that even hours after someone has consumed drugs and the drugs subsequently metabolized, performance can be degraded.

Other accidents have also shown the adverse effects of illegal drug consumption on operator performance. For example, in the 1991 train accident discussed in Chapter 4, in which two freight locomotives had passed a stop signal and inappropriately entered a track reserved for a passenger train, investigators determined that shortly before the accident the engineer and brakeman had ingested marijuana while operating the locomotives.

Investigators concluded that they proceeded beyond the stop signal because they were impaired from the effects of their marijuana consumption.

As with alcohol, high levels of a drug or its metabolites may indicate that the operator is a drug abuser, that is, a long-term user of a drug, or is a drug addict. If an operator is suspected of abusing medications, pharmacy records of prescribed medications may reveal a pattern of use over time. The operator may have approached several physicians and obtained prescriptions from each. The operator also may not have informed his or her employer of either the medication use, or the condition for which the medications were prescribed.

Other information, such as records of convictions for driving while under the influence of alcohol or drugs, may also suggest a pattern of substance abuse (see also Chapter 12). In the United States, the Federal Aviation Administration requires pilots to report such infractions, and reviews the driving records of all pilots to learn of such offenses, regardless of their self-reports (McFadden, 1997). A substance abuse specialist evaluates all pilots with two or more convictions (and some with one), to determine whether they are chemically dependent. Only after these specialists have reviewed the operator's history and concluded that he or she would likely refrain from future drug or chemical use, does it grant the medical certificate needed to serve as a pilot.

Company-maintained personnel records may contain information reflecting an operator's history of substance use. Prolonged absences, or absences at the beginning and end of work weeks or work periods, may indicate chemical use. Performance appraisals may also show marked changes in work habits or work performance—another indicator of chemical dependency (see Chapter 12). Depending on the industry, regulators may require operators to provide the results of regular medical examinations and their medication use. These records should provide investigators with considerable information regarding medical and pharmaceutical antecedents to error.

Specific Impairment

Many of the tasks that operators perform require acute vision or hearing, or subtle senses of touch. Impairment in any of these sensory modalities may lead to errors. Operators in most complex systems are expected to demonstrate sufficient visual acuity to read displays from their control stations, see motion and depth, and distinguish among colors both within and outside of the immediate environment. They should also be able to demonstrate sufficient aural acuity to identify various alerts, recognize electronic and voice communications and other system-related sounds, and determine the direction from which the sounds originated.

Yet, operators may not always recognize their own impairment and even when they do, they may deliberately withhold that information if they believe that reporting the impairment could adversely affect their careers. Investigators acknowledged this in 1996 when a passenger train operator

failed to stop the train he was operating at a red stop signal. His train struck another train ahead, killing him and injuring more than 150 passengers (National Transportation Safety Board, 1997a). Investigators learned that for almost 10 years, the operator had been treated for diabetes, and that he had undergone corrective surgery for diabetic retinopathy, an eye disease brought on by diabetes. They attributed his failure to stop to impaired vision; he was unable to distinguish the signal colors. Although required to do so, he did not inform his supervisors of his medical condition, and despite the impairment, he continued to serve as a train operator.

Depending on the complex system and the sensory modality involved, impairment may be so subtle that neither operators nor their supervisors recognize it, becoming evident only in unusual or unexpected conditions. Investigators encountered this in an investigation of a 1996 air transport aircraft accident in which the captain, who was attempting to land at New York's LaGuardia Airport, lost depth perception on landing, substantially damaging the airplane, although all onboard escaped serious injury (National Transportation Safety Board, 1997b).

The captain had been intermittently wearing monovision contact lenses for several years without incident, lenses that corrected near vision in one and distant vision in the other eye simultaneously. However, in certain visual conditions, the differences in the contact lenses degraded his depth perception. The final moments of the flight path had been over water and through fog, conditions that obscured background features, until just above the runway. The reduced visual cues in the prevailing visual conditions, with the adverse effects of the monovision lenses, sufficiently reduced his depth perception to the point that he allowed the aircraft to descend too low and strike the runway.

Behavioral Antecedents

Behavioral antecedents, which develop from the operator's near- or long-term experiences, can adversely affect performance. They can, for example, follow profoundly stressful events; such as the loss of an immediate family member. The grief and stress of people in these situations, and the effects of that stress on their performance, are understandable.

Many have encountered the effects of behavioral antecedents at one time or another and can attest to their adverse influence. The effects they exert on the performance of an operator in question, however, may be different from that on another's performance. Two behavioral antecedents, fatigue and stress, are of particular interest to error investigators. Others, that are company influenced, may also be important in terms of focusing on operator antecedents.

The Company's Role

Because of the role of the company in the conduct of its operations, antecedents that may appear to be related to the operator may be more correctly attributed to the company. Operators may commit errors because of skill or knowledge deficiencies, and these deficiencies may serve as *the* antecedents to *the* errors in question. But companies that employ the operators establish minimum qualification levels, hire applicants whom they believe will meet those qualifications, and train and certify them as qualified to safely operate their systems. Consequently, because of a company's role in overseeing its operations, company antecedents and not operator antecedents may influence errors that result from a lack of operator knowledge or skills. Companies may also be considered to have influenced operator performance if company-established work schedules led to operator fatigue. If, however, operators engaged in personal activities that led to their fatigue, then the company would not be considered the source of the fatigue and the antecedent to error. This will be discussed more fully in Chapter 6.

Fatigue

Fatigue and its adverse effects on human performance have been studied extensively (e.g., Costa, 1998; Gander et al., 1998; Mitler and Miller, 1996; Rosekind et al., 1994). The research shows that fatigue degrades human performance and can contribute to or cause error. Dawson and Reid (1997a, b) found that those who had been awake as long as 18–27 hours continuously exhibited cognitive performance decrements that were equivalent to having a BAC of 5% or greater.

In a study of accidents in several transportation modes, the National Transportation Safety Board examined the role of fatigue in transportation safety (National Transportation Safety Board, 1999). As investigators conclude,

> Researchers have studied factors that affect fatigue, such as duration and quality of sleep, shiftwork and work schedules, circadian rhythms, and time of day. Cumulative sleep loss and circadian disruption can lead to a physiological state characterized by impaired performance and diminished alertness. Fatigue can impair information processing and reaction time, increasing the probability of errors and ultimately leading to transportation accidents. (pp. 5 and 6)

The importance of the effects of fatigue on cognitive performance of operators, and their effectiveness in complex system operations, has increased as technology has advanced. As Fletcher et al. (2015) write,

> The nature of work-related fatigue has changed over time. For example, in predominantly agricultural times, work tended to be mostly physical

> and fatigue was therefore likely to be largely physical in nature. After industrialization, work in many settings became repetitive and fatigue increasingly included psychological or cognitive components from factors such as time on task. When electricity became widely available and night work more common, sleep and circadian factors underlying fatigue became prominent. (p. 7)

Fatigued operators can have particularly adverse influence on system safety as is evident from a substantial body of literature, albeit primarily focusing on highway drivers. Teran-Santos et al. (1999) found that drivers with untreated obstructive sleep apnea were more likely to be involved in highway accidents than comparable drivers who did not have the condition, after controlling for pre-accident alcohol and drug use, among other factors. Williamson et al. (2011) identified a link between fatigued performance and highway accidents, errors among hospital staff, and workplace injuries such as on construction sites.

Investigators determined that fatigue led pilots of a DC-8 cargo flight to commit critical errors in a 1993 accident at the United States Naval Air Station in Guantanamo Bay, Cuba, in which the crew allowed the airplane to turn too steeply and strike the ground just before landing (National Transportation Safety Board, 1994). The three pilots had been sleep-deprived at the time of the accident. The captain had received only 5 hours of sleep in the previous 48 hours and had been awake for 23.5 hours at the time of the accident. The first officer had been awake for 19 hours continuously and had gotten only 10 hours of sleep in the 57 hours before the accident.

In general, fatigue results from sleep loss in a 24-hour period, accumulated sleep loss over several days, disrupted circadian rhythms, and extended time performing a task. Most people need about 8 hours of sleep daily, give or take 1 hour. Thus, those who receive less 7 hours of sleep in any 24-hour period, or even 8 hours if they are typically need 9 hours of sleep, will likely be fatigued. The greater the difference between the number of hours a person needs to sleep and the amount that person obtained in the preceding 24 hours, the more likely that person will be acutely fatigued.

People can be chronically fatigued from accumulating a sleep debt, that is, not getting the amount of sleep needed to be rested, over several days. Again, assuming that most people need 8 hours of sleep nightly, those sleeping 6 hours a night or less for a week will likely be chronically fatigued by the end of the week, as any parent of an infant can attest.

Most people maintain regular activity schedules and they tend to get tired and hungry about the same time each day. When their schedules are disrupted, for example, by transoceanic air travel or by shifting work schedules, they will have difficulty sleeping during the "new" night, what had been the day in the "old" time zone, no matter how fatigued they are. Several hours later, during the day in the "new" time zone, they may be unable to remain alert, despite coffee, tea, exercise, or other technique that had otherwise been

effective in restoring alertness. Thereafter, they may experience similar sleep disturbances upon their return, when they must readjust to the "old" time zone after having become acclimated to the "new" one.

Many physiological and behavioral functions, including sleep cycle, digestion, hormonal activity, and body temperature, are regulated in approximate 24-hour cycles. Disrupting these functions, as occurs to transoceanic airline travelers and shift workers who work days one week and nights the next, is also fatiguing because the change in schedules is more rapid than is the body's ability to adjust. The experience is known as circadian desynchronosis, popularly referred to as "jet lag."

Circadian desynchronosis makes it difficult for people to sleep when they would otherwise be awake, and to be awake and alert during times when they had been asleep. Disrupted circadian rhythms lead to chronic fatigue, until the body adjusts to the new schedule and the person receives sufficient rest to compensate for the sleep deficits (e.g., Tilley et al., 1982). Because circadian rhythms do not adjust rapidly, a person whose circadian rhythms have been disrupted may be fatigued for days afterward, depending on the extent of the difference between the previous and current schedules. Therefore, although it may be early afternoon local time, a period in which operators would otherwise be alert, operators experiencing circadian desynchronosis may still be performing as if it were 3:00 a.m. Dawson and Fletcher (2001) and Fletcher and Dawson (2001), studied the effects of circadian desynchronosis on employee performance, and developed a scheduling model, which considers circadian effects, to schedule duty times of shift workers or transoceanic workers to minimize their disruptive effects. They found that considering circadian factors in scheduling worker's activities can reduce the effects of circadian disruptions.

Certain medical conditions and medications can also be fatiguing. Sallinen and Hublin (2015) noted that sleep disorders such as obstructive sleep apnea, and pain-related conditions, are fatiguing. Untreated sleep apnea, a condition caused by blockage of a person's airways while sleeping, results in numerous awakenings, of which the person may be unaware, because of the inability to breathe. Akerstedt et al. (2011), noted that about 5% of the adult general population has sleep apnea, about 5%–10% has restless leg syndrome, and about 3.9% has periodic limb movement, all medical conditions that lead to fatigue. In addition, prescribed medications used to treat restless leg syndrome, pain, anxiety, and insomnia, among others, are either fatiguing or lead to decrements in cognitive performance that resemble that of fatigue.

Further, the quality of sleep is not constant; people sleep most deeply between 3:00 a.m. and 5:00 a.m. in their local time zones. They also experience an equivalent decrease in alertness 12 hours later, between 3:00 p.m. and 5:00 p.m. local time. With these phased changes in sleep quality, the likelihood of committing errors also changes. Monk et al. (1996) found that the number of errors committed in a variety of performance measures, errors

that can be directly related to operator performance and to accidents, varies with the time of day. In a study of on-the job injuries in several factories, Smith et al. (1994) found that night shift workers were injured on the job significantly more often than were day shift workers who performed the same tasks for the same employers. The evidence demonstrates that time of day can affect performance, and the times in which operators are most likely to commit errors occur when they would otherwise be in their deepest sleep cycles, between 3:00 and 5:00 a.m., and the afternoon correlate of those hours, between 3:00 and 5:00 p.m.

Alertness is critical to error-free performance in complex systems and fatigue has been demonstrated to degrade operator performance in those cognitive skills that are most needed for operator effectiveness. Gunzelmann et al. (2011) and Lim and Dinges (2008) showed that fatigued individuals have difficulty with sustained attention. Lim and Dinges (2010) found that the cognitive responses of fatigued individuals slowed, that is, they took longer to notice environmental and situational features over that of non-fatigued ones. Akerstedt (2007) found that critical aspects of cognitive performance, such as vigilance, memory, and reaction time, among others, were worse among fatigued individuals than it was for those who were adequately rested. Wickens et al. (2015) observed that complex cognitive performance, such as mental arithmetic and critical reasoning, declined with extended sleep deprivation. Performance decrements were found to be worst during subjects' circadian lows.

Causes of Fatigue

For our purposes, fatigue results from operator-related antecedents or organization- or regulator-related antecedents. Medical conditions that the operator is aware of but does not report to his or her company or the regulator, if required to do so, are an example of a type of operator-related antecedent. However, if the company or the regulator is aware (or should be aware) of the adverse influence of fatigue on cognitive performance and does not require operators with sleep apnea or other medical condition to be diagnosed and treated for the condition, then the antecedent would be considered company- or regulator-related. As information about the deleterious effects of fatigue and fatiguing medical conditions has increased, companies and regulators have increased their role in requiring those in safety-sensitive positions with these conditions to be diagnosed and treated for the conditions.

Otherwise, operators who, for example, are fatigued because they remained awake longer than they had planned to before going on duty, would be considered to be responsible for the antecedents. If they did so in order to watch a film or an event on television, for example, this would almost be considered a violation rather than an error antecedent. However, if they had insufficient sleep for reasons that had little to do with their volition, such as infant care or brief illness, they deserve more consideration, but nevertheless, must be

considered to be the source of the antecedent if they were fatigued as a result of their situations, and did not alert their supervisors to that effect.

Companies and organizations can be responsible for the antecedents of an operator's fatigue if, as noted, they did not require their operators to be treated for fatigue-inducing medical conditions, prohibit their use of impairing over-the-counter and prescribed medications, or if they created fatiguing work schedules. As Fletcher et al. (2015) note, the nature of complex systems today calls for 24-hour operations. These systems are simply too expensive, and the societal costs of their nonoperation is too high, to allow them to cease operations for any length of time. Internationally operating aircraft and vessels, nuclear power stations, and chemical refineries, for example, cannot avoid nighttime operations without causing significant disruption to themselves and to society in general.

Investigating Fatigue

Unlike medical conditions, where medical records describe diagnoses, or alcohol-related impairment, where blood alcohol level provides evidence of the degree of intoxication, fatigue is a particularly challenging metric to assess. As Price and Coury observe, "historically, fatigue has been notoriously difficult to define and operationalize" (2015, p. 86). Because no physical measure of fatigue can be taken, investigators must assess the degree of fatigue indirectly. They do this by assessing evidence for fatigue, relating it to the type of error the operator committed, and determining the likelihood of other antecedents accounting for the error (Price and Coury, 2015; Strauch, 2015).

Investigators determine that an operator's error was the result of fatigue by first establishing that the operator was fatigued. Medical records that demonstrate that an operator has an untreated, fatigue-producing medical condition, would be sufficient to establish that he or she was fatigued. Similarly, evidence of the use of a sedating medication would also be sufficient. Absent such evidence, investigators establish the presence of fatigue by examining the quantity, regularity, and quality of the operator's sleep in the period before the accident. Ideally, a week's worth of sleep/awake times would establish beyond question the quantity and regularity of someone's sleep, but most people have difficulty remembering more than a few days previously what times they went to bed and what time they arose. Therefore, investigators typically ask operators to note their sleep/wake times for 72–96 hours before an accident. This record will establish whether an operator was subject to circadian disruption, and whether he or she got the desired 8 hours, plus or minus 1 hour, of sleep. Irregularity in sleep schedules, and sleep times less than the person's regular sleep hours serve as evidence of fatigue. Obviously, the greater the deficit from 8 hours, the greater the irregularity in sleep/wake times, and the greater the cumulative deficit over time, the more likely the operator was fatigued. In addition, Price and Coury (2015)

highlight the importance of documenting sleep quality. An operator who has accrued sufficient sleep (i.e., around 8 hours), with regularity in the time before an accident, but whose sleep was diminished by noise, interruptions, high temperature, and so on, will be considered to have received insufficient quality sleep and hence, to have been fatigued.

Once an operator has been identified as having been fatigued at the time of the accident, investigators then determine whether the error or errors were consistent with someone who was fatigued. In general, we look for cognitive errors in which the operator misdiagnosed something, or was late in doing a previously completed task, that is, was late or improperly performed a cognitive task that he or she had completed effectively beforehand. For example, failure to properly diagnose something, whether a component failure or a navigation error, can be the result of any of several factors. A person who is fatigued, however, will likely have difficulty shifting attention among possible explanations or components, while focusing excessively on a single item. Because proper diagnosis requires an understanding of a system and its subsystem operations, effectively understanding the nature of a malfunction within the system calls for the operator to rapidly examine the system and recognize the symptoms of the malfunction. Because cognitive activity is slowed when someone is fatigued, evidence of such slowing in cognitive performance would be consistent with someone who is fatigued. Similarly, someone who fails to quickly recognize a change in situational cues, or who is late is performing a task because he or she was late to recognize the need to perform the task, would provide evidence of being fatigued. On the other hand, action errors are typically not related to fatigue. Someone who turns on one switch while intending to activate another, adjacent one, has committed an error that may or may not be influenced by fatigue.

Because the types of cognitive errors prone to fatigue can also be affected by other antecedents, it is necessary to exclude other potential antecedents that could also account for an error to determine conclusively that fatigue led to an error. These include shortcomings in training, oversight, selection, and procedures. For example, an operator who misdiagnosed the cause of a component failure may have lacked the knowledge of the component and its relationship to the system to enable him or her to effectively understand its cause. This lack of knowledge must be excluded as a potential error antecedent, along with other antecedents that can explain the misdiagnosis in order to identify fatigue as the error's antecedent. Only when all potential antecedents of the error have been ruled out, and fatigue is the only plausible antecedent remaining, can one confidently identify the operator's fatigue as the antecedent of the error in question.

Preventing Fatigue

As noted, the cause of an operator's fatigue may lie either with the operator himself or herself, or with the company or regulator. In either instance,

companies or regulators can or have undertaken rule changes, scheduling changes, and education activities, among others, to mitigate opportunities for operators to oversee system operations when fatigued (e.g., see Gander, 2015). For example, after a 2009 airplane accident that killed all 49 passengers and crew onboard and one person on the ground (National Transportation Safety Board, 2010), the U.S. Federal Aviation Administration changed its hours of service rules for pilots to account for duty time served during pilots' circadian lows, that is, times when they would have ordinarily have been asleep. Pilots who worked a period of time that would ordinarily not have been fatiguing, were required to have additional rest hours if that duty time was served at night (FAA regulation 14 CFR Parts 1–27). Many regulators of complex systems require operators to accrue sufficient rest after their duty periods, but few account for changes in the schedules of their duty periods, or for rapid transmeridian time zone changes, as is the case with long-haul transport pilots. Consequently, the rules may allow operators to accrue what would otherwise be adequate rest periods, but because of potential shift changes that lead to circadian disruption, for example, shifting from day shift to night shift, the operator will likely be fatigued in the immediate nights following the schedule change, as the body takes several days to adjust the circadian rhythms to such dramatic changes.

The Federal Aviation Administration, in its revised hours of service rules, encouraged airlines to adopt fatigue risk management systems, which it explained is "a data-driven process and a systematic method used to continuously monitor and manage safety risks associated with fatigue-related error" (14. CFR 171.3). Fatigue risk management systems allow companies the flexibility to develop schedules of work that address the unique risks of their own operations, based on data that the company must collect and analyze. Researchers have described the benefits of such programs (e.g., Dawson et al., 2012; Fletcher et al., 2015), and implementing a fatigue risk management system or similar program that identifies and addresses the risks of operators being fatigued while on duty can reduce, if not eliminate, the role of the company or regulator as an antecedent of an operator's fatigue-related error.

Stress

The effects of stress on performance have been studied extensively. Definitions of stress vary, but the definition by Salas et al. (1996) will be used presently. They define stress as, "a process by which certain environmental demands evoke an appraisal process in which perceived demand exceeds resources and results in undesirable physiological, psychological, behavioral or social outcomes" (p. 6).

The effects of individual stressors depend largely on the person and how stressful he or she perceives them. Stressors that are perceived to be

moderate can enhance performance by counteracting the effects of boredom or tedium in settings in which little changes (Hancock and Warm, 1989). However, stressors considered severe can degrade performance.

Person-Related Stress

Personal stress, influenced by circumstances unrelated to an operator's job that cause "undesirable physiological, psychological, behavioral or social outcomes," are differentiated from system-induced stress. Operators may encounter more than one stressor simultaneously, both person- and system-related, and their performance may be affected by both. The more stressors a person experiences, the more likely that person's performance will be degraded by their effects.

Person-related stressors include marital breakups, the illness or death of family members, or disruptions to routines such as a move or the departure of a household member. The effects of personal stress on an operator's performance can be seen in a marine accident that occurred when a tugboat pushing a barge on the Delaware River, in Philadelphia, ran over a tour vessel (National Transportation Safety Board, 2011). Two of the passengers on the tour vessel were killed in the accident. The operator of the tug/barge, the mate, was unable to see the tour vessel because he was using his cellphone and laptop computer, from a lower level wheelhouse, while operating the vessel. As investigators describe, the mate, who was operating the tug/barge, had told a company official after the accident that … "he had been 'consumed' with dealing with this family crisis; medical records obtained by the National Transportation Safety Board confirmed that the mate's child, who was undergoing a scheduled routine medical procedure that day, had suffered a potentially life-threatening complication less than an hour before the mate went on duty." (p. 17) Investigators held him responsible for causing the accident, but it is nonetheless likely that the stress of learning of his son's life-threatening condition affected his ability to recognize that he needed to inform company supervisors that he could not safely operate the vessel because of the stress that he was experiencing. Instead of properly operating the vessel, he was below a deck that would have enabled him to view the vessel's forward path, and was talking on his cell phone and using his laptop, presumably to obtain more information about his son's condition.

Person-related stressors may not necessarily be negative; they can result from what most consider happy occasions. Alcov et al. (1982) compared the accident rates of U.S. Navy pilots who had experienced stressful life events to those who had not, events that included marital problems, major career decisions, relationship difficulties, job-related problems, as well as impending marriage and recent child birth in the immediate family. Pilots who had experienced stressful events had sustained higher accident rates than pilots who had not. Despite these findings, it is important to recognize that the

mere presence of person-related stressors does not imply that an operator's performance was adversely affected by stress because of the noted individual variations in reaction to stressors.

System-Induced Stress

Operators may find unexpected system events to be stressful, such as displays with information that cannot be interpreted, unexpected aural warnings, and controls that appear to be ineffective. Operator reaction to these stressors is influenced by their experiences and previous encounters with similar events. Operator actions can also lead to stress, particularly if severe consequences might result. The more adverse the consequences, the greater the stress the operator can be expected to experience when encountering that event.

Case Study

On February 12, 2009, a Bombardier DHC-8-400, on a flight from Newark, New Jersey, to Buffalo, New York, crashed into a residence near Buffalo, while the airplane was on its final approach to the airport. All 49 passengers and crew onboard the airplane and one person on the ground were killed in the accident (National Transportation Safety Board, 2010). Night visual meteorological conditions prevailed at the time and nothing untoward was found wrong with the airplane. Investigators concluded that the captain had inappropriately responded to a stick shaker alert, which occurs when an airplane is about to stall. Rather than lowering the nose and advancing power, as he had been trained to do, he pulled the nose back and the airplane entered a stall, from which neither the captain nor the first officer were able to recover. Investigators found that neither the captain nor first officer had effectively monitored the airspeed before the stick shaker had alerted them.

The error in failing to react appropriately to a stick shaker is one that is not wholly consistent with fatigue, given the training that the pilots receive. That is, all pilots are trained and are required to demonstrate their recognition of, and appropriate response to a stall. The stick shaker alert, in which the control column rapidly moves forward and aft and is accompanied by a unique sound, is designed to minimize the time pilots need to recognize the impending stall. Both auditory and tactile cues that are unique to this impending aerodynamic condition are provided and both are readily identifiable. The criticality of rapid recognition and the need for an effective crew response to the warnings of an impending stall led to the requirement for a unique and quickly recognized alert. Consequently, little, if any, diagnosis is

needed to recognize the nature of a stick shaker alert. However, allowing the airplane to approach a stall by failing to monitor the airspeed is an error consistent with fatigue because a proper approach to landing calls for pilots to rapidly shift their monitoring among parameters of airspeed, descent speed, engine power, and lateral and vertical flight paths. However, shifting attention, vigilance, and monitoring are cognitive skills that have been demonstrated to be adversely affected by fatigue.

Neither pilot resided in the city from which the flight originated, and both had "commuted" or flew as a passenger from their residence to Newark. The captain arrived at Newark 3 days before the day of the accident, arriving there in the evening, at 20:05, and began a 2-day trip of flights the next morning. He spent the night before the 2-day trip in the crew room at the airport and awoke before he was required to report for duty at 05:30 the next morning and again the following morning, the day of the accident. In between, he spent the night at a company-paid hotel. The night before the accident, with a 21-hour and 16-minute rest period upon completion of his 2-day trip, he spent the night in the crew room at the airport. Investigators found that 03:10 and again at 07:26 on the morning of the accident he had logged onto the airline's computer. He reported for duty the day of the accident at 13:30.

The first officer flew from her home on the west coast of the United States to Newark, changing planes in Memphis. The flight originated in Seattle at 19:51 local (Pacific) time or 22:51 eastern time and arrived in Memphis at 23:30 Pacific time or 02:30 eastern time. She then took a flight that left Memphis at 04:18 eastern time and arrived at Newark about 06:23, eastern time. She then rested in the crew room from about 07:32 to about 13:05 when she sent a text message from her computer. The flight crews of the flights on which she flew to Newark reported that she slept about 90 minutes on the first flight and for the duration of the second.

Airport crew rooms are provided to pilots and flight attendants to enable them to relax before their flights. Little privacy is available and, while couches may be provided, these are not designed for crew sleeping because the room lights are typically bright and there is little effort to soften the volume of noise. Crewmembers meet each other and typically converse before their flights. Therefore, pilots who spend the night in airport crew rooms may obtain sufficient sleep to be considered rested, but the quality of sleep obtained would negate potential benefits of sufficient hours of sleep, if it were possible for crewmembers to sleep the entirety of their stays in crew rooms. As a result, investigators concluded, "the captain had experienced chronic sleep loss, and both he and the first officer had experienced interrupted and poor-quality sleep during the 24 hours before the accident" (National Transportation Safety Board, 2010, p. 106).

Crew rooms do not charge crewmembers fees for their use, unlike hotel rooms. Regional air pilots, especially first officers, may not earn enough

compensation to be able to afford hotel rooms. Moreover, while regulator hours of service dictate the number of hours and rest pilots much obtain while on duty, the rules do not apply to hours served off duty, as the captain and first officer were on the night before the accident.

The quality of sleep the pilots obtained in the crew room allowed investigators to determine that they were fatigued at the time. However, the error of not recognizing and responding to the impending aerodynamic stall, as noted, was not one consistent with fatigue. In this case, the captain had a record of previous errors in training consistent with the one that led to the accident. Simply put, his record was such that such an error was consistent with the quality of his performance as a pilot when faced with unusual or unexpected events. The first officer, by contrast, had no such record of performance deficiencies. Although investigators determined that the crew was fatigued at the time, the lack of correspondence between fatigue and the error of not recognizing and responding appropriately to a stick shaker, and the presence of an alternative antecedent to error, that is, the captain's poor performance record, prevented them from attributing the critical crew error to fatigue. As they concluded,

> Evidence suggests that both pilots were likely experiencing some degree of fatigue at the time of the accident. However, the errors and decisions made by the pilots cannot be solely attributed to fatigue because of other explanations for their performance…The captain's errors during the flight could be consistent with his pattern of performance failures during testing, which he had experienced throughout his flying career. (National Transportation Safety Board, 2010, p. 107)

Summary

Two general categories of operator antecedents, behavioral and physiological, can lead to error. Physiological antecedents can impair performance either temporarily or permanently, through disease, medications, or alcohol or over-the-counter or illicit drugs. These can temporarily impair operators by altering perception, slowing reaction time, and causing fatigue, among other adverse effects.

Behavioral antecedents to error include fatigue and stress, originating from the operator's personal experiences or from company actions. Long work schedules, changing shift work schedules, abrupt change in time zones, or a combination of these, are company actions that can cause fatigue, well-documented antecedents to error. Stress can be caused by factors related to the job, or events in an operator's personal life that are independent of the job.

DOCUMENTING OPERATOR ANTECEDENTS

MEDICAL CONDITIONS

- Review operator medical records, both company maintained and those maintained by a personal health care provider, with a health care professional.
- Note recent diagnoses of and treatment for medical conditions, and determine the possible effects of the conditions and associated medication on operator performance, in consultation with an occupational health expert.
- Interview colleagues, associates, relatives of the operator, and the operator if possible, to determine if he or she was experiencing even a mild illness or temporary discomfort at the time of the event.
- Interview operator family and colleagues to determine if they noted changes in the operator's daily routines, behaviors, or attitudes, and when these changes were first observed.
- Review company personnel records to detect changes in work habits, job performance, and attendance.

DRUGS OR ALCOHOL

- Request, as soon as possible after the occurrence, a blood sample from the operator, or from the pathologist if the operator was killed, for a toxicological analysis.
- Ask local law enforcement authorities to recommend a reputable and qualified laboratory that can conduct toxicological analyses if local government laboratories are unable to do so.
- Review positive toxicological findings with an occupational health specialist, another toxicologist, or health care provider with the necessary expertise. Ask him or her to obtain and review the results of controlled studies on the medications in question.
- Give the toxicologist information about the care of the body or the specimen if the operator has been killed, the state of the operator's health before the event, and possible medication that the operator may have been taking.
- Consult a physician, pharmacist, toxicologist, or a pharmacologist to learn about the effects of single or multiple drugs on operator performance when evidence confirms that an operator took medications before an occurrence.

FATIGUE

- Document the time at which the operator went to sleep and awoke with the previous 3–4 days before an accident.
- Determine from medical records and prescription drug records or a toxicological sample, if possible, if the operator had an untreated sleep disorder or other fatiguing medical conditions, or had taken sedating medications.
- Assess fatigue from either an untreated sleep disorder, other fatiguing medical conditions, or the use of a sedating medication.
- Characterize those who receive 4 or more hours less sleep than typical in a 24-hour as acutely fatigued and those who receive 2 hours less sleep than usual over four 24-hour periods to be chronically fatigued.
- Reconstruct the times the operator went to sleep and the times the person awoke for each of the days since the travel commenced, using the home time zone as the standard for those who have traveled across time zones.
- If the operator had traveled before the accident, note the number of days that the traveler was away from the base schedule, and the number of days since the traveler returned to the base schedule.
- Document the time of the accident to determine whether it occurred between 3:00 a.m. to 5:00 a.m. local time.
- Identify characteristics of fatigue in the critical errors, including preoccupation with a single task, slowed reaction time, and difficulty performing tasks that had been performed effectively before.
- Assess fatigue, if not medical or medication-related, from an irregular sleep/wake schedule in the days before the accident, or insufficient rest in that period.
- Determine if the error the operator made was a cognitive one, and if so, whether it was consistent with a fatigue-related error.
- Exclude other potential error antecedents such as training shortcomings, inadequate oversight, or a record of poor performance.

AUTOPSIES

- If the operator was killed in the accident, and his or her medical condition is unknown, arrange for an autopsy by a forensic pathologist if possible, or one with additional training and experience in accident investigations.

- Give the pathologist information on the nature of the accident, the state of the body, the role of the operator at the time, the nature of the machinery with which the operator was interacting, and data obtained from medical records, peer interviews, and other sources.
- Provide the pathologist with photos of the operator's body and of the accident site.
- Ask the pathologist for information on preexisting physiological conditions, the effects of impact forces, (if in a vehicle or other dynamic environment) thermal injuries, or toxic fumes, and the presence of corrective lenses, hearing aids, or other supplemental devices on the body of the operator.

STRESS

- Interview family and colleagues to determine whether the operator experienced stressors before the event, and how he or she reacted to them.

References

Akerstedt, T. 2007. Altered sleep/wake patterns and mental performance. *Physiology and Behavior*, 90, 209–218.

Akerstedt, T., Philip, P., Capelli, A., and Kecklund, G. 2011. Sleep loss and accidents—Work hours, life style, and sleep pathology. *Progress in Brain Research*, 190, 169–188.

Alcov, R. A., Borowsky, M. S., and Gaynor, J. A. 1982. Stress coping and the U.S. Navy aircrew factor mishap. *Aviation, Space, and Environmental Medicine*, 53, 1112–1115.

Allen, G. J., Hartl, T. L., Duffany, S., Smith, S. F., VanHeest, J. L., Anderson, J. M., Hoffman, J. R., Kraemer, W. J., and Maresh, C. M. 2003. Cognitive and motor function after administration of hydrocodone bitartrate plus ibuprofen, ibuprofen alone, or placebo in healthy subjects with exercise-induced muscle damage: A randomized, repeated-dose, placebo-controlled study. *Psychopharmacology*, 166, 228–233.

Costa, G. 1998. Fatigue and biological rhythms. In D. J. Garland, J. A. Wise, and V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 235–255). Mahwah, NJ: Erlbaum.

Coury, B. G., Ellingstad, V. S., and Kolly, J. M. 2010. Transportation accident investigation: The development of human factors research and practice. *Reviews of Human Factors and Ergonomics*, 6, 1–33.

Dawson, D., Chapman, J., and Thomas, M. J. W. 2012. Fatigue-proofing: A new approach to reducing fatigue-related risk using the principles of error management. *Sleep Medicine Reviews*, 16, 167–175.

Dawson, D. and Fletcher, A. 2001. A qualitative model of work-related fatigue: Background and definition. *Ergonomics*, 44, 144–163.
Dawson, D. and Reid, K. 1997a. Fatigue, alcohol and performance impairment. *Nature*, 388, 235.
Dawson, D. and Reid, K. 1997b. Equating the performance impairment associated with sustained wakefulness and alcohol intoxication. *Journal of the Centre for Sleep Research*, 2, 1–8.
Fletcher, A. and Dawson, D. 2001. A quantitative model of work-related fatigue: Empirical evaluations. *Ergonomics*, 44, 475–488.
Fletcher, A., Hooper, B., Dunican, I., and Kogi, K. 2015. Fatigue management in safety-critical operations: History, terminology, management system frameworks, and industry challenges. *Reviews of Human Factors and Ergonomics*, 10, 6–28.
Gander, P. H. 2015. Evolving regulator approaches for managing fatigue risk in transport operations. *Reviews of Human Factors and Ergonomics*, 10, 253–271.
Gander, P. H., Rosekind, M. R., and Gregory, K. B. 1998. Flight crew fatigue VI: A synthesis. *Aviation, Space, and Environmental Medicine*, 69, Section II, B49–B60.
Gunzelmann, G., Moore, L. R., Gluck, K. A., Van Dongen, H. P. A., and Dinges, D. F. 2011. Fatigue in sustained attention: Generalizing Mechanisms for time awake to time on task. In P. L. Ackerman (Ed.), *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications* (pp. 83–101). Washington, DC: American Psychological Association.
Hancock, P. A. and Warm, J. S. 1989. A dynamic model of stress and sustained attention. *Human Factors*, 31, 519–538.
International Civil Aviation Organization. 1993. *Human Factors Digest No. 7: Investigation of Human Factors in Accidents and Incidents*. ICAO Circular 240-AN/144. Montreal, Canada.
Lim, J. and Dinges, D. F. A. 2008. Sleep deprivation and vigilant attention. *Annals of the New York Academy of Sciences*, 1129, 305–322.
Lim, J. and Dinges, D. F. A. 2010. A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. *Psychological Bulletin*, 136, 375–389.
McFadden, K. L. 1997. Policy improvements for prevention of alcohol misuse by airline pilots. *Human Factors*, 39, 1–8.
Mitler, M. M. and Miller, J. C. 1996. Methods of testing for sleeplessness. *Behavioral Medicine*, 21, 171–183.
Monk, T. H., Folkard, S., and Wedderburn, A. I. 1996. Maintaining safety and high performance on shiftwork. *Applied Ergonomics*, 27, 17–23.
National Institute on Drug Abuse. 1999. *Cocaine abuse and addiction*. Bethesda, MD: National Institutes of Health Publication No. 99-4342.
National Transportation Safety Board. 1989. *Aircraft Accident Report, Trans-Colorado Airlines, Inc., Flight 2286, Fairchild Metro III, SA227AC, N68TC, Bayfield, Colorado, 1988*. Report Number: AAR-89-01. Washington, DC: National Transportation Safety Board.
National Transportation Safety Board. 1994. *Aircraft Accident Report, Uncontrolled Collision with Terrain, American International Airways Flight 8808, Douglas DC-8-61, N814CK, U.S. Naval Air Station in Guantanamo Bay, Cuba, August 18, 1993*. Report Number: AAR-94-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997a. *Railroad Accident Report, Near Head-On Collision and Derailment of Two New Jersey Transit Commuter Trains, Near Secaucus, New Jersey, February 9, 1996*. Report Number: RAR-97-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997b. *Aircraft Accident Report, Descent below Visual Glidepath and Collision with Terrain, Delta Air Lines Flight 554, McDonnell Douglas MD-88, N914DL, LaGuardia Airport, New York, October 19, 1996*. Report Number: AAR-97-03. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1999. *Safety Report, Evaluation of U.S. Department of Transportation Efforts in the 1990s to Address Operator Fatigue*. Report Number: SR-99/02. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2000a. *Highway Accident Report, Collision of Greyhound Lines, Inc. Motorcoach with Tractor Semi-Trailers on the Pennsylvania Turnpike, Burnt Cabins, Pennsylvania, June 20, 1998*. Report Number: HAR-00-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2000b. *Safety Recommendations I-00-001–I-00-004, January 13*. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2010. *Loss of Control on Approach, Colgan Air, Inc., Operating as Continental Connection Flight 3407, Bombardier DHC-8-400, N200WQ, Clarence Center, New York, February 12, 2009*. Report Number: AAR-10-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2011. *Marine Accident Report, Collision of Tugboat/Barge Caribbean Sea/The Resource, with Amphibious Passenger Vehicle DUKW 34, Philadelphia, Pennsylvania, July 7, 2010*. Report Number: MAR-11-02. Washington, DC: National Transportation Safety Board.

Price, J. M. and Coury, B. G. 2015. A method for applying fatigue science to accident investigation. *Reviews of Human Factors and Ergonomics*, 10, 79–114.

Rosekind, M. R., Gander, P. H., Miller, D. L., Gregory, K. B., Smith, R. M., Weldon, K. J., Co, E. L., McNally, K. L., and Lebacqz, V. 1994. Fatigue in operational settings: Examples from the aviation environment. *Human Factors*, 36, 327–338.

Ross, L. E. and Mundt, J. C. 1988. Multiattribute modeling analysis of the effects of a low blood alcohol level on pilot performance. *Human Factors*, 30, 293–304.

Salas, E., Driskell, J. E., and Hughes, S. 1996. Introduction: The study of stress and human performance. In J. E. Driskell and E. Salas (Eds.), *Stress and human performance* (pp. 1–45). Mahwah, NJ: Erlbaum.

Sallinen, M. and Hublin, C. 2015. Fatigue-inducing factors in transportation operators. *Reviews of Human Factors and Ergonomics*, 10, 138–173.

Smith, A. P. 1990. Respiratory virus infections and performance. *Philosophical Transactions of the Royal Society of London*, 327, 519–528.

Smith, L., Folkard, S., and Poole, C. J. M. 1994. Increased injuries on night shift. *Lancet*, 344, 1137–1139.

Strauch, B. 2015. Investigating fatigue in marine accident investigations. *Paper presented at the 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences*, Las Vegas, NV.

Teran-Santos, J., Jimenez-Gomez, A., Cordero-Guevara, J., and Cooperative Group Burgos-Santander. 1999. The association between sleep apnea and the risk of traffic accidents. *New England Journal of Medicine*, 340, 847–851.

Tiffany, S. T. 1999. Cognitive concepts of craving. *Alcohol Research and Health*, 23, 215–224.

Tilley, A. J., Wilkinson, R. T., Warren, P. S. G., Watson, B., and Drud, M. 1982. The sleep and performance of shift workers. *Human Factors*, 24, 629–643.

Weiler, J. M., Bloomfield, J. R., Woodworth, G. G., Grant, A. R., Layton, T. A., Brown, T. L., McKenzie, D. R., Baker, T. W., and Watson, G. S. 2000. Effects of fexofenadine, diphenhydramine, and alcohol on driving performance: A randomized, placebo-controlled study in the Iowa driving simulator. *Annals of Internal Medicine*, 132, 354–363.

Wickens, C. D., Hutchins, S. D., Laux, L., and Sebok, A. 2015. The impact of sleep disruption on complex cognitive tasks: A meta-analysis. *Human Factors*, 57, 930–946.

Williamson, A., Lombardi, D. A., Folkard, S., Stutts, J., Courtney, T. J., and Connor, J. L. 2011. The link between fatigue and safety. *Accident Analysis and Prevention*, 43, 498–515.

Zacny, J. P. 2003. Characterizing the subjective, psychomotor, and physiological effects of a hydrocodone combination product (Hycodan) in non-drug-abusing volunteers. *Psychopharmacology*, 165, 146–156.

6

The Company

> The Japanese nuclear accident three weeks ago occurred largely because managers counted on workers to follow rules but never explained why the rules were important.
>
> **Wald, 1999**
> *New York Times*

Introduction

A company's role in creating antecedents to error has been increasingly recognized. The *New York Times* account of the 1999 accident at a Japanese uranium processing plant suggests that the operator errors that led to the accident were a direct result of management actions and decisions. A subsequent *New York Times* article revealed that plant managers compounded the effects of their initial actions by not developing an emergency plan in the event of an incident (French, 1999). Apparently, the managers believed that an accident could not occur and therefore, none was needed. This chapter will address how companies can create antecedents to error in the systems that they oversee and operate.

Organizations

Companies operating complex systems can influence the safety of those systems in many ways. They hire and train the operators, establish operating rules and maintenance schedules and practices, and they oversee compliance with these rules, schedules, and procedures, among other activities. Shortcomings in any of these areas have the potential to create error antecedents, and companies are ultimately responsible for ensuring that their actions minimize the role of potential antecedents, so that the systems they operate do so safely.

Hiring

Companies hire the individuals who operate their systems. In doing so, the standards they use can have considerable influence on the safety of system operations. Selecting operators who may not be effective will not only be expensive in training costs, but it can enhance the likelihood of subsequent errors occurring as well.

Companies generally consider several factors when selecting candidates for operator positions. These include requisite skills and knowledge, predicted performance as operators, and the number of operators needed to oversee system operations.

Skills, Knowledge, and Predicted Performance

Companies are expected to identify the knowledge and skills their personnel need to effectively operate systems. They apply these to their hiring standards to enable them to identify applicants likely to perform the required tasks safely and those applicants predicted to commit a disproportionate number of errors.

For example, maintenance technicians would be expected to perform one or more of the following tasks,

- Read and understand maintenance manuals
- Understand the structural and mechanical relationships among components and subsystems
- Apply instructions to tasks
- Identify and locate appropriate components and tools
- Diagnose and correct mechanical malfunctions
- Recognize when the tasks have been completed
- Complete written documentation
- Describe, either orally or in writing, the maintenance actions taken
- Verify that the intent of the maintenance instructions had been carried out

Deficiencies in performing any of these tasks could lead to errors. The more critical skills an applicant can perform, the more effective the applicant will likely be as an operator, and the fewer the errors he or she will be expected to commit. It is a company's responsibility to ensure that those it hires as maintenance technicians, for example, can do so competently, either upon hiring or after completing a training program. Selecting a person for a position of responsibility without the requisite training to enable that person to perform acceptably creates an antecedent to error.

Companies have also created error antecedents by selecting operators based on skills or experience that may not necessarily relate to those actually

needed for system operations. For example, because interpersonal skills are critical to the effectiveness of operator teams, companies need to consider these skills among their selection criteria, skills that may not always be effectively assessed through company selection criteria. Members of operator teams possessing deficient interpersonal skills may commit errors, or contribute to the errors of others.

In industries in which the regulators establish operator-licensing criteria, companies apply them as minimum selection standards, limiting but not eliminating their ability to implement their own selection standards. In the event that investigators identify deficiencies in the skills of licensed operators, they need to focus on both the regulator's licensing standards and the company's hiring criteria to identify antecedents to error.

The Number of Operators

The number of operators interacting with a system, whether too many, too few, or optimum, affects the quality of individual and team performance and system safety. Paris, Salas, and Cannon-Bowers (1999) believe that an insufficient number of operators can create excessive operator stress because of the resultant increased individual workload. However, hiring too many operators is wasteful and can create low individual workload, which can lead to operator boredom and inattention, both potential antecedents to error (e.g., O'Hanlon, 1981).

Designers, regulators, companies, or operators themselves may establish the minimum number of persons needed to operate systems. In aviation, regulators require at least two pilots to operate air transport aircraft, even if only one is needed to effectively control the airplane. Companies in other systems may have more discretion in determining the number of operators they need. They may base the decision on the nature of the tasks, the degree of difficulty in performing the tasks, the amount of time available to complete them, or even on existing agreements with labor organizations. For example, when scheduling maintenance tasks, companies may want to return the equipment to service quickly and may assign more operators than usual to the task.

In some systems, operator activity during different system operating phases varies and as a result, additional operators may be needed more in certain operating phases than at other times. Some companies determine the number of operators they need based on an "average" workload level. In other systems, where individual workload varies according to the system operating phase, companies may match the number of operators to the number needed by the operating phases. During periods of high workload, they may add operators to match the workload and likewise, they may reduce the number needed during low workload periods. For example, air traffic control sectors or airspace segments are often combined at night when air traffic activity is typically light, thereby reducing the number of controllers needed during those low activity periods.

Researchers have studied methods of determining the number of operators needed to operate safely. Lee, Forsythe, and Rothblum (2000) developed a mechanism to determine the appropriate number of operators needed in one complex system, commercial shipping. They incorporated factors such as phase of voyage (open waters, restricted waters, and in port), port call frequency, level of shore-based maintenance support, and applicable work/rest standards into their analysis. The number of crewmembers needed varied considerably with changes in these factors, factors that would have different weights according to the particular system and its operating environment.

Training

In general, operator performance deficiencies are more likely to result from deficiencies in company training than from deficiencies in hiring. Training programs significantly affect the ability of companies to reduce error opportunities and decisions made on the type and length of training can influence the potential for errors to occur in system operations.

Training in complex system operations generally involves two components. One, initial training, designed to convey the overall knowledge and skills necessary to effectively operate the systems, is administered to newly hired operators and two, ongoing training (or recurrent training in commercial aviation), is designed to maintain the skills and knowledge of existing operators and introduce them to changes in the system or to other safety-related topics. Most companies that operate complex systems employ some type of initial training to introduce newly hired operators to system operations, however, not all conduct ongoing training.

Training Content

After companies have hired candidates to serve as system operators, they need to provide them with knowledge of the system and its operating procedures, and enable them to acquire the skills necessary to operate the system. Some companies employ on-the-job training to accomplish these objectives. In such training, new employees first observe experienced operators and then, over time, learn to operate the system under their supervision. Other companies use formal training curricula to train new operators.

Initial training should describe the system, its components and subsystems, their functions, normal and non-normal system states, and general company policies and operating procedures. Initial training can also introduce employees to potential system shortcomings. New systems, no matter how thoroughly tested before their introduction to the operating environment, may have difficulties or “bugs” that designers had not anticipated and therefore, not addressed. Although training should not be expected to compensate for design deficiencies, the training environment may be used

to introduce operators to potentially unsafe elements of system operation so that they will be familiar with them and, if necessary, respond appropriately should they encounter these elements.

Ongoing training is designed to ensure that system operators learn about design changes, new and/or modified operating procedures and regulations, and other pertinent system changes to enable them to continue to perform effectively. Some industries require ongoing training at regular intervals, others schedule it only as needed, and some do not conduct additional training at all. Similar differences can be found among the standards accrediting organizations apply to the certification of professionals in their particular fields (Menges, 1975). Some establish criteria for ongoing training, including the curricula, instructional media, and intervals between training sessions while others establish a minimum number of continuing education credits or courses to be completed within a certain period.

Instructional Media

Technology has enabled training systems to inform and educate operators in new and innovative ways. For example, simulators can accurately replicate system operating conditions with almost the full range of system characteristics during both expected and unexpected conditions. These allow operators to practice responding in a safe environment free of severe personal consequences to scenarios that would otherwise be too dangerous to practice in actual systems. Despite acquisition costs that can exceed several million dollars (e.g., Moroney and Moroney, 1998) simulators and system training devices have considerably improved operators' ability to respond effectively to nonroutine operating conditions.

Training programs, whether initial or ongoing, may employ various instructional media, including computer-based instruction, CD-ROM, and Internet-based presentations, as well as instructor presentations, and text and written material. Each has particular advantages and disadvantages for students, instructors, and course training coordinators. Some allow more flexibility in a student's pace of learning and some may offer reduced development and delivery costs. Some programs combine instructional media, with available instructors to answer questions on specific topics at the students' own pace, without disrupting the class or distracting other class members.

However, it must be remembered that regardless of the particular medium, instructional media and system training can only deliver instructional material; they cannot compensate for deficiencies in the material they present. Although the type of instructional medium can influence the quality or pace of learning, the quality of the training program is largely dependent upon the content of the material presented and not the instructional medium delivering it.

Costs versus Content

Companies strive to maintain effective training programs within budgetary limitations, yet compromises to balance the competing objectives of high quality with low cost are a fact of corporate life. Companies exercise considerable control over the content of their training programs, within the given regulatory standards, and try to keep costs down, recognizing that effective training in complex systems can be so expensive that they may have to make compromises in other areas as a consequence. Reason (1997) suggests that the need to maintain the operations that produce the resources necessary to fund training influences companies to weigh production needs more than nonproduction needs, such as training.

Because of the often substantial costs of operator training, managers may devote considerable effort to operator selection to ensure that those hired will successfully complete the training. Some companies even require operators to be fully trained before being considered for selection. High training costs may also produce an unintended result—inducing companies to retain operators whose skills may have deteriorated to avoid the expense of training new operators. Such decisions could create company antecedents to error.

The caliber of a company's training serves as a measure of its commitment to reduce opportunities for error. Those that provide training beyond the minimum that the regulator requires, and that spend additional resources to ensure that their operators are skilled and proficient, can be said to have undertaken positive efforts to reduce opportunities for error. By contrast, companies with training programs that meet only minimum standards may create opportunities for error. Issues such as these, reflecting on corporate culture, will be discussed more later in this chapter.

Procedures

Complex systems require extensive rules and procedures to guide operators on how to interact with the equipment, and to serve as the final authority on how operations are to be conducted. Procedures also guide operators in responding to new or unfamiliar situations, and can help to standardize operations across companies and even across international borders. The International Civil Aviation Organization, for example, has established rules governing both air traffic control procedures and aircraft operations across international borders, while its marine counterpart, the International Maritime Organization (IMO), has developed rules and procedures for use in international maritime operations. These two systems, marine and aviation, which involve international operations as a matter of routine, have developed and implemented standard procedures to make compliance with rules and procedures across international borders relatively simple.

To be effective, operators must perceive procedures to be logical and necessary to ensure safe and efficient operations. Otherwise, they may disregard them over time, as reported at the beginning of this chapter—unless their

fear of adverse managerial action is sufficient to ensure their compliance. Designers often develop general operating procedures for the systems they design, but companies are ultimately responsible for the procedures they implement, which they can tailor to their own operational needs and requirements. Companies may modify procedures after they have begun operating the equipment for such reasons as standardizing procedures across the different equipment that they operate, or improving operational efficiency as they gain familiarity and experience with the equipment. Such modifications, in response to lessons learned during system operations, reflect well on a company's oversight and its efforts to enhance operational safety.

General versus Specific

Companies face a fundamental dilemma in developing and implementing procedures. Procedures should be sufficiently specific and unambiguous to guide operators in responding to most situations, yet not so specific that operators may feel unable to respond to unexpected situations for which applicable procedures have not yet been developed. As Flach and Rasmussen (2000) note, "it is impossible to have conventions for unconventional events" (p. 170).

System safety depends on operators following procedures, yet the operators must still possess the authority to bypass procedures if, given their experience and expertise, they believe that the circumstances so warrant. Explicit procedures provide the guidance operators need to operate systems as intended and ensure that different operators control the system similarly. However, overly restrictive procedures can work against safety. Reason (1997) argues that these may actually encourage operators to develop their own shortcuts, circumventing the intent of the procedures. Overly restrictive or comprehensive procedures also need extensive management oversight to ensure that operators comply with them. Most companies recognize that it is impossible to develop procedures for responses to all possible circumstances. Ideally, procedures companies develop and implement will be both comprehensive and specific, applying to as many potential circumstances as possible.

Oversight

Oversight is a critical element of a company's responsibility for the safety of the system it operates. It is intended to both ensure that operators adhere to the operating procedures, and to inform companies of critical aspects of system operations in need of modification. Oversight serves both to inform operators how to operate the system, and to inform companies how

effectively operators are carrying out their procedures, as well as of procedural changes that may be needed to ensure continued operational safety. Effective oversight requires obtaining sufficient operator performance data, through frequent and thorough acts of data gathering and inspection, to recognize how well the system is being operated, and to identify changes that may be needed to enhance operational safety.

Oversight data should describe employee performance quality in a variety of operating conditions. Many large companies, with thousands of operators, have too large a span of supervision to allow effective oversight of all operators, and they depend on operator performance data for effective oversight. Effective oversight informs companies about all critical aspects of their operations. Well-informed companies can quickly respond to operational difficulties as they emerge, and thus help to reduce the likelihood that these difficulties can become opportunities for error.

The quality of oversight varies according to the system, the operating conditions, the operators, and the severity of the consequences of operator error. Since continuous oversight of operators is unfeasible, companies must maximize the quality of their oversight, through as many of the operating cycles as reasonable, to provide them with sufficient information for a realistic portrayal of the quality of operator performance and procedural quality. Done properly, operational oversight can be effectively carried out by monitoring, recording, and sampling data that is representative of performance in the various system operating phases. For example, to determine the extent of taxpayer compliance with the tax code in the United States, the federal government inspects or audits the tax returns of fewer than 5% of taxpayers in a given year. Yet, this sampling of taxpayers reveals that the overwhelming majority of taxpayers comply with the tax laws, despite the low probability that an individual's returns will be audited. Most taxpayers know that they will receive stiff penalties if convicted of evading tax laws and they are unwilling to face the penalties, irrespective of the low risk of being caught. By sampling a few tax returns the federal government can maintain realistic oversight of taxpayer compliance with tax laws.

New Operators

Companies need to respond to operator performance deficiencies before their performance can jeopardize system safety. Consequently, operators with manifestly deficient performance are rarely encountered in complex systems; companies tend to address the issue before safety is jeopardized. Organizations that fail to deal with deficient performance can create antecedents to error and investigators may occasionally encounter operators with histories of performance deficiencies.

Many companies place new operators in probationary periods that give them full discretion to evaluate operator performance, and retain or

discharge operators in these periods. Effective oversight requires companies to identify and address performance shortcomings that their operators may demonstrate at any time during their employment, but companies should pay especial attention to employees who may have difficulty mastering skills during their probationary period because of the relative ease with which companies can deal with probationary employees compared to employees retained beyond their probationary periods.

Experienced Operators

Some experienced operators can present different types of safety challenges to companies. They may perform satisfactorily during routine or expected situations but perform unacceptably when encountering nonroutine or emergency situations. Effective oversight should enable companies to identify those operators whose ability to respond to nonroutine situations is uncertain. Investigators, to the extent possible, should obtain company records of operator performance during both routine and nonroutine operating periods, as well as records of company responses to operator performance deficiencies.

Some operators may also knowingly violate company procedures when they are confident that company managers will not detect their actions, thereby endangering system safety. Here too companies must identify and respond to such safety hazards. Because of the need to ensure that operators are following necessary procedures, companies that take little or no action in response to unjustified violations of procedures create antecedents to error by effectively communicating to operators that procedural noncompliance will not be addressed. Ultimately, companies may have to remove from safety-sensitive positions operators who have disregarded operating procedures.

Investigators observed the outcome of such an operator in their investigation of a 1993 aircraft accident, involving a pilot whom peers had reported as ignoring critical procedures (National Transportation Safety Board, 1994). The airplane, owned and operated by the Federal Aviation Administration, struck the side of a mountain, killing him and two of his peers onboard, before air traffic controllers could clear the plane to climb through clouds to a higher altitude and safely depart the area. The pilot chose not to delay takeoff to wait on the ground for air traffic controllers' authorization to proceed to his destination, most likely in the belief that he could obtain it more readily once airborne.

After the accident, pilots who had flown with the captain described to investigators multiple instances of his unsafe practices, reports that corresponded to the nature of his performance on the accident flight in his willingness to violate rules and procedures. According to the investigators, his fellow operators reported that the pilot had (National Transportation Safety Board, 1994),

> Continued on a VFR [visual flight rules] positioning flight into IMC [instrument meteorological conditions],
> Conducted VFR flight below clouds at less than 1,000 feet above the ground in marginal weather conditions [violating safe operating practices],
> Replied to an ATC [air traffic control] query that the flight was in VMC [visual meteorological conditions] when it was in IMC,
> Conducted departures without other flightcrew knowing essential flight planning information, such as IFR [instrument flight rules]/VFR/en route filing/weather briefing/ultimate destination or routing,
> Departed on positioning flights without informing other crewmembers whether he had obtained weather information or filed an appropriate flight plan,
> Disregarded checklist discipline on numerous occasions,
> Refused to accept responsibility that his failure to adhere to a checklist had caused an engine damage incident in January 1993, [an event that precipitated a letter of reprimand from his supervisors],
> Performed a "below glide path check" in IMC when VMC conditions were required by FIAO [the FAA organization operating the flight] requirements, and refused to answer a SIC [co-pilot] query regarding the reason for his alleged violation of VFR requirements in an incident 2 weeks before the accident. (p. 8)

Moreover, investigators were informed of reports that other pilots had made to the captain's supervisors regarding the captain's procedural violations. Yet, despite repeated complaints, the supervisors failed to address his performance. Their failure allowed him to continue violating procedures as he did on the accident flight—continued visual flight operation into instrument conditions—without air traffic control authorization. Consequently, investigators determined that the supervisors' role in this accident was equivalent to that of the captain's. While their action did not directly lead the accident, their inaction in the face of considerable information about his unsafe practices allowed the pilot to knowingly violate a procedure that caused the accident. As Reason (1997) notes, opportunities for "rogue" operators to ignore procedures increase in organizations that have deficient oversight, or have managers who are unwilling or unable to enforce compliance with the organization's operating rules and procedures.

"Good" Procedures

By establishing the circumstances under which operators interact with the systems, and by setting the tone for their "corporate culture," companies and organizations can positively affect operator performance. They can encourage operators to keep management informed of perceived safety hazards, including instances of operator noncompliance with operating procedures.

Reason (1997) recommended several techniques that companies can undertake to enhance the safety of system operations, including establishing a

"reporting culture," in which companies encourage employees to report safety issues. Such reports, which can include an operator's own errors, when conveyed in a fair and nonpunitive atmosphere, can encourage operators and their supervisors to recognize and address system antecedents to error, thus serving as a critical component of a corporate culture that enhances a company's operational safety. Companies can also develop and implement salary and incentive programs that reward suggestions for improving safety. Where technical capabilities are in place, companies can read data from system recorders to monitor system state and operator performance. All have increased supervisor knowledge of potential safety issues in their operations.

Formal Oversight Systems

Since Reason (1990,1997) offered suggestions to enhance system safety, researchers have examined and regulators and companies have developed and implemented specific techniques to this end. For example, Helmreich and his colleagues studied techniques to expand crew resource management (CRM) practices to include error management (e.g., Klinect, Wilhelm, and Helmreich, 1999) and Guldenmund's (2010) and Grote's (2012) studies of corporate safety culture suggest techniques that companies can use to enhance safety. Today, international and domestic regulators have endorsed concepts to proactively enhance safety and have published manuals to assist companies to develop and implement them (International Civil Aviation Organization, 2002, 2013).

Line Operations Safety Audit

Line Operations Safety Audit or LOSA, was derived from Helmreich and his colleague's research into CRM (e.g., Klinect, Wilhelm, and Helmreich, 1999). In LOSA, expert observers observe real world system operations ("line operations"), and record crew actions and statements, both technical and team oriented, according to objective, predetermined assessment criteria. After the observation, the LOSA observers review the results with the operators and provide feedback on the technical and team-oriented quality of their performance, with suggestions for improvement, when warranted. LOSA is not designed to be used negatively, such as for criticizing or adversely rating performance, but rather constructively, to improve performance and enhance operational safety.

Flight Operations Quality Assurance

Flight Operations Quality Assurance (FOQA), as LOSA, was developed initially in aviation but has since been implemented in other complex systems

as well. FOQA uses software to analyze system recorder data, such as data on flight data recorders, not for accident investigation purposes for which they were developed, but to monitor operator performance of the systems in question (Federal Aviation Administration, 2004). Flight data recorders, which had recorded five parameters in the analog era (heading, altitude, airspeed, vertical acceleration, and microphone keying), now record hundreds of digital aircraft system and flight parameters that give precise indications of the airplane, it's state in the minutes before the accident, and pilot interactions with aircraft controls and major systems. Reading out flight data recorders proactively enables airlines, as with LOSA, to monitor operator performance in certain maneuvers at particular airports, for example, and to determine whether additional training and/or procedural modifications are needed. FOQA provides airline information, in the absence of an accident or incident, about operator and aircraft performance in real time, with multiple pilot crews and aircraft, allowing them to learn of potential safety issues in the absence of an accident or incident, or in the absence of operator or management recognition of potential safety issues. Since airlines have begun implementing FOQA, other industries with onboard system recorders, such as companies operating oceangoing vessels that are required to be equipped with voyage data recorders, have begun similar initiatives as well.

Safety Management Systems

Safety Management Systems (SMS) are structured programs that enable companies to identify and mitigate risks to enhance the safety of their systems. Unlike the previous two programs, SMS was developed initially in the marine system, when, in 1993, the IMO made the implementation of these programs mandatory, in response to the March 6, 1987, Herald of Free Enterprise ferry accident off the coast of Belgium, in which 188 passengers and crew were killed (Department of Transport, 1987). An SMS program is a systematic method of recognizing and mitigating risks in company operations. Since its adaption in the marine industry other systems, such as aviation, have encouraged companies to implement SMS programs as well. The Federal Aviation Administration (FAA, 2015) describes four elements of SMS programs: management policies, procedures, and organizational structures that accomplish the desired safety goals; a formal system of hazard identification and safety risk management; controls to mitigate the risks (safety assurance); and a method of promoting safety as a core corporate value.

These are among the methods that companies across different complex systems can use to proactively enhance safety. Companies and systems have employed programs that may be unique to the particular systems, or to the companies. It is important to note, however, that such programs are meant to be proactive and that investigators should not consider their absence, unless

mandated by the regulator, to be indicative of an organizational antecedent to error.

Company Errors

Researchers have examined differences between errors that can be attributed to an individual operator and those attributed to a company and its operations. For example, Goodman, Ramanujam, Carroll, Edmondson, Hofmann, and Sutcliffe (2011) describe conditions that must be met for errors to be considered organizational:

> First unintended deviations from organizational expectations…[regarding] work activities; second, the…actions of multiple individuals who are acting in their formal organizational roles and working toward organizational goals; third, [both of which]…can potentially result in adverse organizational outcomes; and, finally, [both of which] are primarily caused by organizational conditions. (p. 154)

That is, for an error to be organizational and not individual, more than one individual had to have been involved in acting or deciding, in a manner considered to be furthering an organization's goals, in ways that would lead to adverse consequences.

Strauch (2015), expanding on this concept, adds that to identify company antecedents, one of three conditions have to be met. Investigators must be able to demonstrate that company officials (1) acted or made decisions in the face of information alerting them to the need for different actions or decisions, (2) acted or decided in the face of self-evident information of the need for corrective action, or (3) took no action or made no decision when an action and/or decision was warranted.

Information on the need for corrective action can include a history of similar accidents or incidents in a relatively brief period, operator or manager reports of safety deficiencies, FOQA, LOSA, and SMS data, regulator-cited infractions, patterns of failures on operator examinations of proficiency, and patterns of maintenance deficiencies. In the face of such evidence, company action to address the information provided is warranted and inaction should be considered a company antecedent to error. Illustrations of self-evident data include work schedules that are fatigue-inducing, punitive oversight programs, and publicly berating operators who commit errors.

Unfortunately, illustrations of organizational accidents are not common in the investigation literature; identifying them as such is a relatively recent phenomenon. Whether it is not acting on indications of safety shortcomings, deciding not to improve training when data calling for such improvement

is manifest, or tolerating bullying management, investigators have come to recognize and describe companies' roles in accidents.

Case Study

On July 25, 2010, a 30-inch-diameter segment of a petroleum pipeline ruptured near Marshall, Michigan (National Transportation Safety Board, 2012). The rupture was caused by a defect in a weld in the pipeline. Operators in the company's Edmonton, Alberta, Canada, pipeline control center failed to detect the rupture for over 17 hours, in spite of multiple indications of a pipeline fault near Marshall, Michigan. Rather, they interpreted the aural alerts and visual display information not as a rupture but as a separation in a column of oil in the pipeline, a result, they believed, of the effects of hilly terrain on the column of petroleum within the pipeline. While such terrain is known to cause column separation, because gravitational forces differentially effect oil flow within a pipeline with changes in terrain, the location of the leak was in a relatively flat area and the control center operators, all from Alberta, were unfamiliar with the terrain in Michigan. As a result of their misinterpretation of the alerts and displays, the operators continued pumping oil through the ruptured pipeline on two separate occasions, for over 1½ hours, until they were informed of the leak by personnel in Michigan, 17 hours after the initial rupture. Only upon notification from those near the site of the rupture were they able to correctly recognize that a pipeline rupture had occurred. Over 800,000 gallons of crude oil were released into the adjacent wetlands and a nearby creek and river. The cost of the cleanup, which continued over a year after the accident, exceeded $1 billion USD.

Investigators found several company antecedents that led to the controller and supervisor failures to detect the rupture. Procedures developed specifically to insure that ruptures would be detected were violated. For example, controllers were required to stop oil flow after 10 minutes if alarms continued. However, in the belief that additional pressure from the pumps would join the separated oil column, pumping was allowed to continue well beyond that limit. In addition, the performance of the operator teams—and of the teams of operators and their supervisors—broke down, resulting in ambiguous supervisory chains, in which supervisors deferred decisions to subordinates who lacked the necessary expertise, limiting the team's ability to effectively analyze the rupture-related alarms and displays. Further, investigators found that training exercises that the company had conducted for operators were invariant, and over time, the exercises failed to present the controllers with realistic scenarios that could have prepared them to effectively diagnose and respond to system anomalies.

"They have some preconfigured programs," one controller told investigators, "that we run and some of them have station lockouts and some of them have leaks and some of them have just com [communications devices] fails and different scenarios that we go through to help us to understand what we're seeing" (National Transportation Safety Board, 2012, p. 48). In addition, control center supervisors were not required to take the recurrent training that the operators had been required to take, yet they nonetheless played key roles in analyzing, incorrectly, the post-rupture alarms and displays. These safety lapses, as well as similar findings that investigators obtained in previous investigations of company incidents, had been known to control center supervisors and company managers, but they were not addressed. In fact, investigators found that supervisors had used the lessons of earlier incidents to justify bypassing and violating company procedures in the Marshall, Michigan, accident. Company supervisors and operators had information regarding the need for alternative courses of action, yet they did not act on them, thereby creating antecedents to the errors of the operators and their supervisors. This accident illustrates the types of antecedents that a company can commit that led to operator (and supervisor) errors, which exacerbated the effects of the rupture, creating a serious environmental accident.

Summary

Accident investigators as well as students of human error have come to recognize the role of companies that operate complex systems in creating antecedents to errors in those systems. The selection processes used to hire system operators can identify recognizable or predictable operator skills and deficiencies, and thus influence safety by the quality of operators they hire. Companies determine the optimum number of operators needed to run their systems during both routine and non-routine system states, they train operators to safely operate the systems, and they conduct recurrent training to enable operators to remain current with changes in system design or operating procedures. Companies also establish operating procedures and, within reason, enforce adherence to those procedures. Procedures should guide operators to interact with systems throughout the range of expected system states, yet provide sufficient flexibility to operators in the event that the procedures do not apply to an unexpected event. Several systems have developed and implemented programs to proactively enhance safety. Companies that have information of the need to address safety deficiencies but don't act on them, or where safety lapses in system performance are such that companies should but don't act on them regardless, are considered responsible for antecedents to errors in their systems.

DOCUMENTING COMPANY ANTECEDENTS

- Refer to company manuals and related written documentation, interview managerial and operations personnel, human resource specialists, experienced operators, and both newly hired operators and if possible, applicants who were not hired, to obtain their accounts of the selection process, training, procedures, and oversight.

SELECTION

- Determine the extent to which both the company's selection criteria and selection process changed over a period of several years.
- Match company-employed selection criteria to the skills that operators are expected to perform routinely. Note inconsistencies between the two, and determine the extent to which the process can adequately predict effective operator performance among applicants.
- Assess the extent to which the company recognizes operator deficiencies during their probationary period and after they have fully qualified as operators.
- Determine the number and proportion of operators in each of several years from the time of the accident, who were not retained beyond the conclusion of their probationary periods, or whose employment was terminated thereafter, because of performance deficiencies.
- Describe performance deficiencies that led to the company actions.

TRAINING

- Compare the content of company training to the knowledge and skills operators need to effectively and safely control systems.
- Document the training material presented, the methods of instruction, and instructional media, such as control station simulators, that the organization uses in training.
- Determine the extent to which the content of company training pertained to the event under investigation.
- Assess the extent to which company training surpasses, meets, or falls below the minimum level of instruction mandated.

PROCEDURES AND OVERSIGHT

- Determine the extent to which the operating procedures that the company established prepared operators to respond to the event being investigated.
- Document the type and frequency of company oversight over a period of time up to the accident.
- Determine the extent to which oversight informed the company of operator application of company procedures.

HISTORY

- Document previous company accidents, incidents, and regulatory violations.
- Document operator reports to the company of safety concerns.
- Document company responses to accidents, incidents, regulatory violations, and/or operator safety concerns.
- Determine the extent to which errors or safety deficiencies resemble previous accidents, incidents, violations, and/or operator safety concerns, and the company's response to them.

References

Department of Transport. 1987. MV Herald of Free Enterprise, Report of Court No. 8074, Formal Investigation. London: Her Majesty's Stationery Office.

Federal Aviation Administration. 2004. Flight operational quality assurance AC No: 120-82. Washington, DC: Federal Aviation Administration.

Federal Aviation Administration. 2015. Safety management systems for aviation service providers AC No: 120-92B. Washington, DC: Federal Aviation Administration.

Flach, J. M. and Rasmussen, J. 2000. Cognitive engineering: Designing for situation awareness. In N. B. Sarter, and R. Amalberti (Eds.), *Cognitive engineering in the aviation domain* (pp. 153–179). Mahwah, NJ: Erlbaum.

French, H. W. 1999. Under pressure, Japanese nuclear workers were lax, report says. *The New York Times*, October 4, 1999.

Goodman, P. S., Ramanujam, R., Carroll, J. S., Edmondson, A. C., Hofmann, D.A., and Sutcliffe, K.M. 2011. Organizational errors: Directions for future research. *Research in Organizational Behavior*, 31, 151–176.

Grote, G. 2012. Safety management in different high-risk domains—All the same? *Safety Science*, 50, 1983–1992.

Guldenmund, F. W. 2000. The nature of safety culture: A review of theory and research. *Safety Science*, 34, 215–257.

International Civil Aviation Organization. 2002. *Line operations safety audit (LOSA)* (Doc 9803 AN/761). Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization. 2013. *Safety management manual (SMM)* (3rd ed.) (Doc 9859). Montreal, Canada: International Civil Aviation Organization.

Klinect, J. R., Wilhelm, J. A., and Helmreich, R. L. 1999. Threat and error management: Data from line operations safety audits. In R. S. Jensen, B. Cox, J. D. Callister, and R. Lavis, (Eds.), *Proceedings of the tenth international symposium on aviation psychology* (pp. 683–688). Columbus, OH: Ohio State University.

Lee, J. D., Forsythe, A. M., and Rothblum, A. M. 2000. *The Use of Crew Size Evaluation Method to Examine the Effect of Operational Factors on Crew Needs*. Report No. UDI-16(1). Seattle, WA: Battelle Seattle Research Center.

Menges, R. J. 1975. Assessing readiness for professional practice. *Review of Educational Research*, 45, 173–208.

Moroney, W. F. and Moroney, B. W. 1998. Flight simulation. In D. J. Garland, J. A. Wise, and V. D. Hopkin, (Eds.), *Handbook of aviation human factors* (pp. 355–388). Mahwah, NJ: Erlbaum.

National Transportation Safety Board. 1994. *Aircraft Accident Report, Controlled Flight into Terrain, Federal Aviation Administration, Beech Super King Air 300/F, N82, Front Royal, Virginia, October 26, 1993*. Report Number: AAR-94-03. Washington, DC.

National Transportation Safety Board. 2012. *Pipeline Accident Report, Enbridge Incorporated, Hazardous Liquid Pipeline Rupture and Release, Marshall, Michigan, July 25, 2010*. Report Number PAR-12-01. Washington, DC.

O'Hanlon, J. F. 1981. Boredom: Practical consequences and a theory. *Acta Psychologica*, 49, 53–82.

Paris, C. R., Salas, E., and Cannon-Bowers, J. A. 1999. Human performance in multi-operator systems. In P. A. Hancock (Ed.), *Human performance and ergonomics* (pp. 329–386). San Diego, CA: Academic Press.

Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Strauch, B. 2015. Can we examine safety culture in accident investigations, or should we? *Safety Science*, 77, 102–111.

Wald, M. 1999. Experts say lapses led to Japan's A-plant failure. *The New York Times*, October 23.

7

The Regulator

> President Park Geun-hye of South Korea vowed on Monday to disband her country's Coast Guard, saying that South Korea owed "reform and a great transformation" to hundreds of high school students who died in a ferry disaster last month.
>
> **Choe, 2014**
> *New York Times*

Introduction

In one form or another, regulators are essential components of complex systems. They provide a degree of assurance to the public that the complex systems it depends upon are safe, and they regulate the systems to ensure that minimum standards of safe operation are maintained. Regardless of the complexity of a particular system or a system with operational safety measures with which people may be unfamiliar, a government agency is typically responsible for overseeing the safety of the system. Whether one boards an airplane or a ferry, or turns on an electrical appliance that receives its electrical power from nuclear energy, an agency of some kind regulates the particular industry. Throughout the world, some level of independent supervision and inspection of complex systems has become expected. In the United States, with some exceptions, federal agencies carry out the oversight. In Australia, individual states oversee the railroads.

The level of regulator oversight over a company's operations varies among countries, industries, and regulators. Some oversee relatively minute aspects of company operations while others play a less active role in the systems they oversee. In general, the more consequential the potential adverse effects of a system accident, the more likely that a regulator will be involved in overseeing the system.

The importance of the regulator to system safety can be seen in the marine environment. Ferry accidents, in which hundreds of people have been killed, have occurred in countries with large inter-island ferry transportation systems, but with relatively weak regulator oversight. For example, the April 14,

2014, the ferry accident in South Korea involving the ferry Sewol referred to at the beginning of this chapter, killed over 300 passengers. After the accident, allegations arose over lax oversight of the ferry. The agency responsible for overseeing the safety of the vessel was reported to have failed to recognize how changes to the vessel's structural design could affect its stability, which, if true, is a critical regulatory oversight error.

Depending on the industry, regulators establish standards for operator licensing and training, maintenance and inspection, operating procedures, operator medical standards, and in some industries even organizational structure, activities that parallel many of those of organizations and companies. A weak or ineffective regulator communicates to the industry it oversees, and to the operators of that industry, that deficient performance, whether deliberate or inadvertent, will be overlooked.

Given the similarity of the regulator oversight tasks to those of companies, investigators can assess the adequacy and effectiveness of regulator performance, and of regulator antecedents to error, in ways that are similar to those conducted for companies, by examining the role of many of the antecedents previously outlined. For example, the effectiveness of rules governing equipment design features can be gauged by the standards of data conspicuity, interpretability, and other characteristics discussed in the preceding chapter.

What Regulators Do

Regulators primarily perform two functions that are critical to system safety. They establish rules ensuring the safety of system operation and equipment design, and they enforce compliance with those rules. The rules are designed to provide a minimum level of safety to the systems they oversee. Organizations that operate at that level would be expected to operate safely. Of course, exceeding those levels of safety would be encouraged, but not required, by the regulator. Regulator antecedents are either a function of inadequate rules, poor oversight, or both, and investigators must examine whether regulator oversight, in either capacity, led to errors that caused accidents.

Regulators are expected to establish sufficiently rigorous rules, methods, and standards to provide a minimally acceptable standard of public safety. Yet, at the same time, overly restrictive regulations may inhibit operations and thus a company's ability to operate profitably. As a result, regulators face pressures unlike those of other system elements. They are asked to oversee the safety of systems with potentially catastrophic consequences to system malfunction, without restricting the freedom of companies to operate their systems profitably.

Reason (1997) refers to "the regulators' unhappy lot," in which they are caught between demands for absolute system safety, resistance to what may be considered excessive oversight, and a public that is often unwilling to provide regulators the resources necessary to enable them to carry out their missions effectively. As a result, regulators, whose work is effective with continued system safety, rarely attract public attention. Reason (1997) points out that the public may consequently become unwilling to provide the resources regulators need to enable them to conduct the oversight needed to effectively monitor the safety of the systems that they are tasked with overseeing. Since the benefits of effective regulatory oversight are mainly seen in their absence, such as after an accident has occurred, reducing the funding of regulators may appear to be a relatively painless way to reduce the expenditure of public funds while at the same time not inhibiting perceptible levels of public safety. As Reason (1997) notes, this leads to less than satisfactory consequences.

> In an effort to work around these obstacles, regulators tend to become dependent upon the regulated companies to help them acquire and interpret information. Such interdependence can undermine the regulatory process in various ways. The regulator's knowledge of the nature and severity of a safety problem can be manipulated by what the regulated organization chooses to communicate and how this material is presented. (p. 174)

Further, regulators also face pressure to maintain their expertise in the industries they oversee in the face of continued technological advances. As the pace of technological change increases, regulators find it increasingly difficult to effectively evaluate systems and the procedures needed to operate them. Yet, as new hardware and software are introduced into service, regulators are expected to anticipate potential operating errors in the use of the new systems, even if they lack the technical expertise to evaluate them. As Reason (1997) explains,

> Regulators are in an impossible position. They are being asked to prevent organizational accidents in high-technology domains when the aetiology of these rare and complex events is still little understood. (p. 171)

Regulator Activities

Given the two functions of regulators, enacting rules and enforcing those rules, regulator antecedents to error fall into one of those categories. As with other antecedents, investigators must work backward from the error through the system to identify the regulator antecedents to error. The nature of the antecedent determines the resultant error.

Enacting Rules

There tend to be fewer antecedents from regulator shortcomings in the rules that govern the industry than in those related to rule enforcement, because over time, as regulatory shortcomings become recognized, often through accidents, regulators tend to correct the shortcomings rectified by enacting rules that address particular deficiencies. For example, in the 1970s and 1980s, as aviation accidents involving well-designed and well-maintained aircraft due to crew error continued to occur, regulators recognized that pilots needed to be trained in CRM. In response, in 1998, the U.S. Federal Aviation Administration required pilots of air transport aircraft to complete CRM training (Federal Aviation Administration, 2004).

This type of regulatory defiency could be seen in a ferry accident that occurred in New York City in 2003 (National Transportation Safety Board, 2005). The vessel operator experienced what investigators termed an "unexplained incapacitation" as he was about to dock the vessel. As a result, he did not slow the vessel as it neared the dock and it crashed into the dock, killing 11 passengers. The investigation found that the operator had been taking a prescribed pain medication, one of its side effects included seizures, a possible factor in explaining his incapacitation. Yet, the Coast Guard, the federal agency that regulates U.S. Marine operations, had no prohibition in place to warn mariners against using the medication. Nonetheless, fearing suspension of his license, the mariner did not report using the medication to the Coast Guard. As a result, investigators identified shortcomings in the Coast Guard's medical oversight system, but they did not consider those to have played a part in the accident. Investigators identified these shortcomings as safety concerns in their report and recommended that the Coast Guard upgrade its system of medical oversight of mariners to bring it in line with the medical oversight that other federal transportation regulators (such as the Federal Aviation Administration) conducted. To its credit, the Coast Guard agreed and over several years considerably upgraded its system of medical oversight of mariners to a level considered equivalent to that of other transportation regulators.

In some systems, such as aviation and marine, both domestic and international regulators establish rules governing system operations, through agencies that are entities of the United Nations. In aviation, this is carried out by the ICOA and in marine, by the IMO. In both transportation modes, their rules, once adopted, are enforced by countries on behalf of the international regulators, which have no enforcement authority themselves.

When investigating the role of the regulator in an accident, document the applicable regulations and determine whether the errors identified in the accident had been addressed in the existing regulations. Be aware of rules that are so general as to be of little value in actually ensuring safety. For example, pilots in the United States, after an accident due to human error,

can be charged with violating rule 14 Code of Federal Regulations 91.13, for so-called "careless and reckless" operation. The rule states:

a. ***Aircraft operations for the purpose of air navigation.*** No person may operate an aircraft in a careless or reckless manner so as to endanger the life or property of another.

Because the rule does not distinguish between an error due to equipment design or training, oversight, and so on, a pilot involved in any accident in which error played a part can, in effect, be charged with violating this rule.

Enforcing Rules

Antecedents to shortcomings in regulator performance tend to fall in this general category, typically in accidents in which the regulator had information, or should have recognized that an entity's operational safety was deficient. For example, when identifying errors resulting from ineffective training, for example, training that was required to meet certain regulatory standards, investigators should determine whether the regulator training should have recognized and addressed the shortcomings, and if so, why they were not addressed.

Investigators of a marine accident that occurred 4 years after the previously discussed ferry accident similarly identified an operator whose use of prescription medications with impairing side effects played a role in the cause of the accident (National Transportation Safety Board, 2009). Unlike the previous accident, the mariner had informed the Coast Guard of some, but not all, of the drugs he had been taking, but the Coast Guard, which by this time had upgraded its medical oversight system, failed to follow up on the mariner's drug use to determine whether the prescribed medications he had provided information on to the regulator adversely affected his performance (they did).

Because the regulator, the Coast Guard, had information about this mariner's use of impairing prescription medications, and because it had been cited previously for its deficient oversight of mariner medical status but still permitted the mariner to operate while using impairing medications, investigators determined that the regulator had played a role in the cause of the accident. As they wrote: "Also contributing to the accident was the U.S. Coast Guard's failure to provide adequate medical oversight of the pilot in view of the medical and medication information that the pilot had reported to the Coast Guard" (National Transportation Safety Board, 2009, p. 136).

This accident also demonstrates that in an accident a regulator rarely directly causes an error that leads to an accident, as it would, for example, with a company that operated a system unsafely. Regulators do not cause

accidents, but by not preventing companies from operating unsafely regulators can be considered to contribute to accidents rather than cause them. Alternatively, by failing to ensure compliance with its regulations, regulators can be considered to have permitted companies to cause accidents through their own actions (or inactions).

Case Study

Regulators play a role in overseeing the safety of many systems, in addition to the ones that we typically consider. For example, in one famous incident, the regulator of the U.S. financial industry failed to act on information that it had suggesting the need for higher level of enforcement than what it had been providing. On December 10, 2008, Bernard Madoff, a well-respected financier who had headed a leading electronic securities exchange, confessed to his sons that the investment firm that he headed, Bernard L. Madoff Investment Securities, was a Ponzi scheme. A Ponzi scheme is an illegal enterprise in which the operator takes money from one investor and gives it to another, pocketing some of the money for himself or herself, by promising the "investor" high returns on the money provided. The sons alerted the U.S. federal regulator of the financial industry, the Securities and Exchange Commission (SEC), of their father's activities and the next day Madoff was arrested for securities fraud, among other criminal charges. Madoff pled guilty to multiple counts of securities fraud 7 months later, at the age of 76, and was sentenced to 150 years in prison.

Bernard Madoff's fraud was a classic Ponzi scheme, a type of fraud named for Charles Ponzi, who, according to the SEC, defrauded thousands of persons in New England in a phony postage stamp investment scheme (SEC, 2009). Newspaper accounts said that investors lost an estimated $17 billion in the money that they had given Madoff to invest. Counting the paper losses from the fraud, that is, the cash losses with the loss of the income Madoff's fund was alleged to have generated, the total loss that investors sustained was estimated to exceed $60 billion. Among the defrauded investors were close Madoff friends, neighbors, relatives, and the late Nobel Prize winter, Elie Wiesel, who lost his life savings and whose charitable organization lost over $15 million (Strom, 2009) in the scheme.

The SEC establishes financial reporting requirements for and governance of publicly owned corporations, and the trading of equities in those corporations, among its other responsibilities. Its role is vital to the integrity of the U.S. financial system. Ineffective SEC oversight by a regulator that was established by the federal government during the Great Depression to oversee an industry whose fraudulence had led to widespread financial losses of duped

investors, could lead to financial catastrophe, the financial equivalent of a catastrophic accident in a complex system.

After Madoff's arrest, it was learned that the SEC had, on multiple occasions, been informed of suspicions regarding Madoff's trades. Not only had several investors reported their suspicions to the Commission, one had filed three separate, signed complaints and then met with SEC officials to explain why Madoff's purported returns, which he was required to regularly report to the SEC and to his investors, could not have been legally obtained. Further, two periodicals, one, Barron's, a widely read and well-respected U.S. business publication, published articles in May 2001, 7 years before Madoff's arrest, suggesting improprieties with Madoff's securities.

In addition to the suspicions raised by complainants to the SEC and by financial publications, numerous "red flags" or suspicions regarding the nature of Madoff's alleged investments should have been evident to the regulator in its oversight of the Madoff securities company. As investigators of the SEC's failure, its inspector general reported,

- The returns on Madoff's investments were consistent and largely unrelated to actual market performance over a 14-year period, a highly unusual result through several market downturns
- Madoff did not charge fees per trade, as was the Wall Street practice
- His timing of trades, that is, selling before a downturn and buying before the market turned up, was consistently successful, something that is also highly unusual
- The outside auditor of his fund (an SEC requirement analogous to an independent auditor of an SMS system) was his brother-in-law and not a major public accounting firm
- Several investors who considered investing in Madoff's funds, and who then examined the funds closely (conducting "due diligence") using publicly available information, became suspicious of the funds and would not invest in them
- The alleged financial strategy that the Madoff fund employed could not be duplicated by other investors

In response to both the complaints it received and the publication of the articles about Madoff's fund, the SEC conducted at least two examinations of Madoff's securities, one in 2004 and one in 2005. Neither uncovered the Ponzi scheme. How then did the federal regulator responsible for overseeing the U.S. financial industry miss discovering Madoff's fraud, one that was relatively unsophisticated (as are all Ponzi schemes) and one that private investors became suspicious of using publicly available information? To answer this question, the SEC's Office of the Inspector General (OIG), an independent monitor established by the federal government to provide

impartial examinations of the performance of federal agencies, conducted an investigation into the SEC's failures with regard its oversight of Madoff's securities.

What made the SEC's failure particularly troublesome was its history and role in U.S. financial oversight. The SEC had

- Over 60 years of experience in overseeing the financial industry
- Considerable in-house expertise at detecting fraud in the industry
- Promulgated the rules that Madoff was accused of violating

Underlying the OIG investigation was the knowledge that had the fraud been discovered sooner, for example, at the times of its own investigations, investors would have saved billions of dollars in losses because Madoff's activities would have been terminated and many investigators would not have lost their life savings.

The OIG report (SEC, 2009) describes, in considerable detail, the errors of a regulator tasked with considerable responsibility to oversee a vast and complex system.

These included:

- Failing to properly oversee those SEC officials charged with examining Madoff's securities
- Selecting examiners who lacked the necessary expertise to address the allegations against Madoff
- Failing to follow up on overt discrepancies in Madoff's statements to examiners
- Failing to understand the nature of Madoff's alleged financial crimes and not making the effort to understand them
- Failing to recognize the significance of the suspicions raised against Madoff's funds
- Ineffectively communicating findings of one investigation to those conducting the second, resulting in considerable duplicated efforts
- Failing to verify information Madoff provided with readily obtainable information from outside entities that would have demonstrated the deceptiveness of Madoff's claims

The report cited a litany of mistakes and misjudgments that individuals within the agency committed regarding Madoff, including repeated errors by the same persons. Although the report cited errors that, as with many errors, may appear to be inexplicable in hindsight, implicit in the report is the sense that some SEC managers were trying to meet the agency's many responsibilities, in the face of a numerous mandated tasks, with limited resources. Investigators also determined that some SEC personnel, as many outside the

agency, were impeded in their efforts by their difficulty in believing that someone as well-regarded in the financial industry as Bernard Madoff, with many prominent investors among his clients, could have been the perpetrator of a simple Ponzi scheme.

Regulator personnel did not cause the Madoff Ponzi scheme, but they failed to uncover it, despite what was shown to have been considerable available information suggesting the scheme, and in one instance outlining it. This failure was due to bureaucratic shortcomings in the performance of the agency, managers who chose people for the Madoff investigation who lacked the necessary expertise, and thereafter provided them with little guidance and follow up. Further, these managers also failed to understand the nature of the scheme and avoided opportunities to understand it. The failure of the SEC to recognize the fraud, after suspicions regarding Madoff were first raised in the years before the scheme collapsed, cost investors billions of dollars, including many who lost their life savings. The regulator did not cause the fraud, but its failure contributed to its severity.

Summary

Regulators play critical roles in the safety of complex systems. They establish the rules governing the operations of the systems they oversee and they enforce compliance with those rules to ensure system safety. Regulators may establish and enforce rules governing system design, system operation, maintenance, and personnel qualifications. Many of the antecedents relating to equipment design and organizational antecedents apply to regulator antecedents as well. Regulator antecedents to error do not cause accidents directly but, by not preventing organizations from operating unsafe systems, allow errors that can lead to accidents occurring.

Typically, regulator shortcomings arise from failures to enforce rules, rather than from not enacting them. However, in some instances, accidents have occurred in which regulators were shown to have failed to enact adequate rules. In one accident, the regulator did overhaul its oversight system and tighten its rules governing medical oversight, but through inadequate enforcement allowed violations of its rules to lead to a subsequent accident.

DOCUMENTING REGULATOR ANTECEDENTS

- Examine regulator inspector selection criteria and inspector training and determine their competence at assessing the safety of a company's operations.

- Apply the presentation and control design standards outlined in Chapter 4 to assess the quality of the regulator's oversight and approval of the design of equipment used in the system being overseen.
- Determine the extent to which the regulator effectively assessed the technology incorporated in the equipment.
- Evaluate the extent to which the regulator's operator-licensing requirements provided an acceptable level of safe system operation.
- Examine the effectiveness of regulator approval of operating rules and procedures as applied to the circumstances of the event.
- Determine the number of inspections of a company, and the thoroughness of those inspections, to determine the extent to which the regulator met the oversight standards it established.
- Identify information the regulator had, such as previous company incidents, accidents, and rule violations, indicating the need for additional oversight and determine whether additional oversight was conducted.
- Determine how responsive the regulator was in addressing safety deficiencies that it had identified.

References

Choe, Sang-Hun. 2014. South Korea to disband Coast Guard, leader says. *The New York Times*. May 19, 2014.

Federal Aviation Administration. 2004. *Crew Resource Management Training*. AC No: 120-51E. Washington, DC: Federal Aviation Administration.

National Transportation Safety Board. 2005. *Allision of Staten Island Ferry Andrew J. Barberi, St. George, Staten Island, New York, October 15, 2003*. Report Number MAR-05-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2009. *Allision of Hong Kong-registered containership M/V Cosco Busan with the Delta Tower of the San Francisco–Oakland Bay Bridge San Francisco, California, November 7, 2007*. Report Number MAR-09-01. Washington, DC: National Transportation Safety Board.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Securities and Exchange Commission (SEC). 2009. *Investigation of Failure of the SEC to Uncover Bernard Madoff's Ponzi Scheme—Public Version*. Report No. OIG-509. Washington, DC: Securities and Exchange Commission.

Strom, S. 2009. *Elie Wiesel levels scorn at Madoff. The New York Times*, February 26.

8

Culture

> At Korean Air, "such teamwork has been nearly impossible," says Park Jae Hyun, a former captain and Ministry of Transportation flight inspector. Its cockpits have operated under an "obey or else" code, he says. Co-pilots "couldn't express themselves if they found something wrong with a captain's piloting skills.
>
> **Carley and Pasztor, 1999**
> *Wall Street Journal*

Introduction

On August 6, 1997, a Korean Air Boeing 747 crashed into a hill several miles short of the runway in Guam, killing 228 passengers and crewmembers (see Figure 8.1). This accident was the latest in a string of major accidents that investigators had attributed, at least in part, to errors that the airline's pilots had committed (National Transportation Safety Board, 1999).

In the 16 years before this accident the airline had experienced one of the highest accident rates of any airline. These included the following:

- August 1983: A Boeing 747 deviated more than 300 miles off course into Soviet territory before the Soviet Air Force shot it down
- December 1983: A DC-10 crashed in Anchorage after the pilots attempted to take off from the wrong runway
- July 1989: A DC-10 crashed in Libya after the crew mishandled an instrument approach
- August 1994: An Airbus A300 crashed in Cheju, Korea, after the crew landed at an excessive airspeed

Even after the Guam accident, the most serious event the airline experienced since the Soviet Air Force shot down its Boeing 747, pilot error-related accidents continued to plague the airline. These included the following:

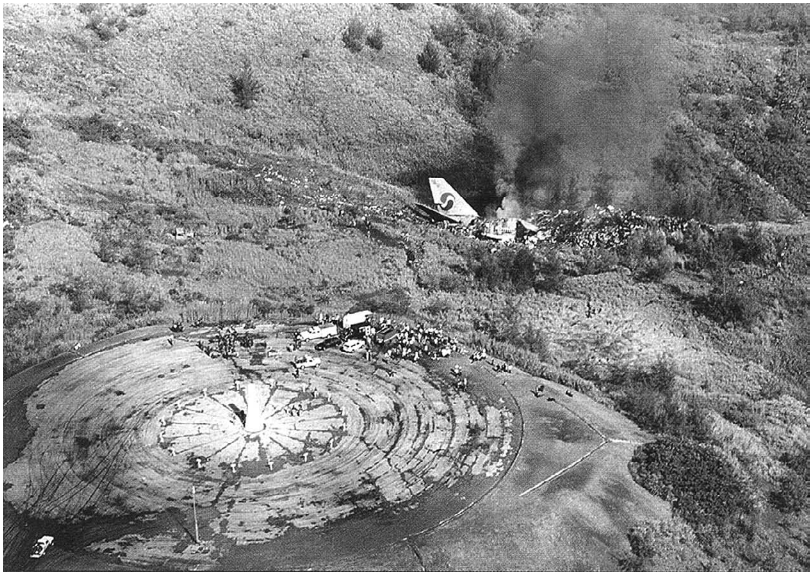

FIGURE 8.1
The site of the Boeing 747 accident in Guam. (Courtesy of the National Transportation Safety Board.)

- August 1998: A Boeing 747 crashed after the captain misused the thrust reverser while landing at Seoul
- September 1998: An MD-80 ran off the end of the runway at Ulsan, Korea
- March 1999: An MD-80 ran off the end of the runway at Pohang, Korea
- April 1999: An MD-11 freighter crashed in Shanghai

In 1999, the *Wall Street Journal* implied that factors rooted in Korean society and culture affected the airline and its safety record (Carley and Pasztor, 1999). The newspaper stated that,

> Korean Air's history has emphasized hierarchy. It is easy to discern the hierarchy: former [Korean] air force pilots, then fliers from other military services, and Cheju men [civilians that the airline trained] at the bottom. Red-stone rings worn by Korean Air Force Academy graduates command instant respect. And ex-military men, while training co-pilots in simulators or during check rides, sometimes slap or hit the co-pilots for mistakes. In the cockpit, friction and intimidation can cause trouble. For a civilian co-pilot to challenge a military-trained captain "would mean loss of face for the captain," says Mr. Ludwin…[a] former Pan Am captain. For the co-pilot, he adds, "it's more honorable to die, and sometimes they do." (Carley and Pasztor, 1999, pp. A1, A2)

The newspaper raised a critical issue by suggesting that specific Korean cultural factors adversely affected the airline's safety. Was it correct in its implication? Can cultural influences serve as antecedents to errors? This chapter will examine cultural factors in complex systems and discuss the relationship of cultural factors to operator performance.

National Culture

Cultural influences affect and are manifested in the behavior of people who work in the same companies, live in the same regions, and belong to the same ethnic groups. Some have suggested that cultural factors affect operator performance (e.g., Orasanu, Fischer, and Davison, 1997) and hence, system safety. "Performance of a plant," Moray (2000) notes, "is as much affected… by the expectations of society, as by the engineering characteristics of the design and the ergonomics of individual work and the design of communication within and between groups and teams" (p. 860).

Schein (1990, 1996) defines a culture as,

> (a) a pattern of basic assumptions, (b) invented, discovered, or developed by a given group, (c) as it learns to cope with its problems of external adaptation and internal integration, (d) that has worked well enough to be considered valid and, therefore (e) is to be taught to new members as the (f) correct way to perceive, think, and feel in relation to those problems. The strength and degree of internal consistency of a culture are, therefore, a function of the stability of the group, the length of time the group has existed, the intensity of the group's experiences of learning, the mechanisms by which the learning has taken place, and the strength and clarity of the assumptions held by the founders and leaders of the group. (1990, p. 111)

The assumptions that Schein refers to are commonly known as norms, ways that people act, perceive, and interpret the values that they share, that may be unspoken but are nevertheless perceived, felt, and practiced by members of a group. Cultural norms are recognized by members of their culture. They help group members understand expectations, customs, and beliefs so that they can facilitate integration, acceptance, and beliefs regarding behaviors. For those outside the culture, they can serve to demarcate exclusion.

Cultural norms help travelers understand how to act when meeting members of a different culture. Cultures can differ in childrearing practices, courtship behavior, and deference to the elderly, for example, and those from different cultures may be uncomfortable with those differences. Avoiding behaviors considered offensive or insulting in different cultures is key to harmonious relations with members of those cultures.

Much of the recent work relating cultural factors to system safety was influenced by Hofstede (1980, 1991), and his study of a multi-national corporation, IBM, then with offices in 66 countries. In the 1960s and 1970s he administered a Likert-type questionnaire to company employees in their offices across the globe. With this type of questionnaire respondents are given statements and asked to agree or disagree with the statements on a scale generally of one, strongly disagree, to five, strongly agree. He found differences on several dimensions of behavior among the employees of the different cultures. One, he termed "power distance," refers to the extent to which people perceive difference in status or power between themselves and their subordinates and superiors. In cultures with high power distance, subordinates and supervisors perceive the differences between them to be greater than do those in cultures that score low on power distance. In those cultures, subordinates would be less willing to confront a superior, or call a superior's attention to an error that he or she may have committed, than would their counterparts in countries with low power distance.

A second dimension, "individualism-collectivism," characterizes the degree to which individuals accept and pursue the goals of the group to which they belong, relative to their own individual goals. An individually oriented person is more self-sufficient and derives more satisfaction from pursuing personal goals than from pursuing group goals. Collectivist-oriented persons identify more with the companies that employ them than do individually oriented persons. They tend to view errors as reflections of the company or group as much as of themselves as individuals.

"Uncertainty avoidance," a third dimension, refers to the willingness or ability of people to contend with uncertain or ambiguous situations. People in cultures with high uncertainty avoidance generally find it difficult to deal with ambiguous or unclear situations that have few applicable procedures. They would be expected to respect and adhere to rules more readily than would their counterparts in cultures with low uncertainty avoidance. Those in cultures that are low in uncertainty avoidance feel comfortable responding to uncertain or novel situations that they had not experienced before, or to situations to which few rules and procedures apply. He labeled a fourth dimension masculinity–femininity. Masculine cultural traits refer to assertiveness and toughness, and are focused on material success. Feminine traits are considered to be more modest and tender, and are concerned with the quality of life.

When Hofstede initially conducted his research China was relatively uninvolved in the global economy and IBM had no offices in China. Since then China has become fully integrated into the world's economy and Hofstede applied his inventory to people in China. The result was a fifth dimension, long-term and short-term orientation (Hofstede and McCrae, 2004). Long-term cultural traits stress thrift and perseverance while short-term orientation, reflecting traditional Asian or Confucian traits, emphasizes social obligations and tradition.

Some researchers have corroborated Hofstede's findings in a variety of settings and identified additional differentiating cultural characteristics (e.g., Helmreich and Merritt, 1998). Maurino (1994) described five cultural dimensions among operators in aviation that are related to those Hofstede identified. These include adherence to authority compared to a participative and democratic approach, inquiry in education and learning as opposed to rote learning, identification with the group rather than identification with the individual, calm and reflective temperament compared to a volatile and reactive one, and free expression and individual assertiveness compared to deference to experience and age.

Helmreich and his colleagues argued that the inability of early CRM programs to substantially impact the quality of operations was due to the influence of cultural factors and the application of a Western crew model of CRM to non-Western cultures. As a result, factors such as the critical role of junior officers in safety, a fundamental precept of CRM, would be difficult to accept in some non-Western cultures that stress rank and status. Helmreich, Merritt, and Wilhelm (1999) and Helmreich, Wilhelm, Klinect, and Merritt (2001) contend that these programs were developed in the United States, but when applied to countries in other cultures difficulties developed. Unlike the United States where CRM programs had originated, organizations found that when CRM programs were implemented in countries where employees scored high on power distance, the junior operators resisted efforts to be more assertive in dealing with their superiors, and senior operators did not accept their subordinates as fully contributing team members, thus negating many of the perceived benefits of CRM programs.

Researchers have applied Hofstede's work to a complex system, military aviation, to assess the relationship between cultural factors and safety. Soeters and Boer (2000) examined the safety records of members the North Atlantic Treaty Organization (NATO), and the air forces of 14 of its member countries. Many NATO pilots operate the same aircraft, and instructors from two of its member countries train almost all of its pilots. The air forces, although distinct, often practice together, follow the same procedures, and use similar criteria to select their pilots. They found a significant relationship between the accident rate of each country and the country's score on Hofstede's cultural dimensions, particularly individualism–collectivism. Countries with cultures that scored high on individualistic traits had lower accident rates than countries considered more group oriented.

Since Hofstede published his findings, his work has come under criticism. Tayeb (1994), criticized the methodology Hofstede employed, while Chen (2008) and Heine, Lehman, Peng, and Greenholtz (2002) criticized both the methodology and the interpretations Hofstede drew from the results of his questionnaire administrations. McSweeney (2002) was perhaps, most detailed in criticism of Hofstede's work. For example, among his criticisms he writes,

> Having assumed that the pertinent response differences were caused by national values, Hofstede then supposes that the questionnaire response differences are decipherable manifestations of culture (cf. Kreweras, 1982; Smucker, 1982; d'Iribarne, 1991). Despite the criticisms above of (this) assumption…let us temporarily assume it to be correct. It requires another analytical leap to assert that the cause may be identified through its assumed consequences. Disregarding this problem, Hofstede obfuscates the questionnaire response differences with national culture. (p. 104)

Hofstede (2002) responded to McSweeney's criticism point by point, going as far as to label him an "accountant" as his academic appointment was in a business college. Overall, the criticisms of Hofstede's work essentially address the datedness of the research, noting how much society and cultures have changed since the 1960s and 1970s when Hofstede collected much of his data, and the difficulties inherent to ascribing cultural dimensions to the results of Likert questionnaires.

In truth, the criticisms have some validity. It is difficult to conceive of a researcher today who would label a cultural dimension as masculinity–femininity and ascribe to the feminine side such traits as modesty and tenderness. Moreover, to ethnographers and anthropologists, who spend extensive time inhabiting the cultures they study in order to observe, identify, and document norms and cultural traits, identifying cultural traits based on the results of a quickly completed questionnaire is difficult to accept. Thus, Hofstede's dimensions can be criticized because they have remained static while cultures have continued to evolve, and because of the difficulties in the method used to derive them. Nonetheless, his work is still widely accepted by researchers and accident investigators who may intuitively accept the dimensions because of their simplicity and the virtue of their ready application to common observations of cultural differences. Ultimately, Sondergaard (1994) applied what may be an effective way to determine the validity of Hofstede's work. "The widespread usage of Hofstede's culture types beyond (the number of) citation(s)," he writes (p. 447), indicates "…validation of the dimensions by empirical research."

National Cultural Antecedents and Operator Error

Regardless of what one thinks of Hofstede's work and that of others who have employed questionnaires to identify cultural factors, the presence of cultural differences is widely accepted (e.g., Morris and Peng, 1994; Nisbett, Choi, Peng, and Norenzayan, 2001; Klein, 2005). The influence of cultural factors on system operations are evident; they influence a variety

of operator–equipment interactions, and can make the difference between effective and erroneous performance. Nonetheless, identifying cultural factors as antecedents of operator error is difficult. For one, language differences, and difficulty in an operator's communicating in a language different from his or her mother tongue, may account for shortcomings in training and oversight. Further, linking an error to a cultural factor, which may have been subject to considerable criticism for the manner in which it was derived, is not easily accomplished. The factor has to be established by reputable research and be widely accepted. Further, because of the potential presence of other factors that can serve as error antecedents, the difficulty of ascribing errors to cultural factors is made even more difficult. Korean Air may have sustained a high accident rate because of cultural factors for example, but shortcomings in training and oversight, which may have had little to do with Korean cultural factors, may have adversely operator performance as well.

Strauch (2010) raised an additional difficulty with ascribing error causation to cultural factors. "The very potential of sociotechnical systems for intense time pressure and severe consequences from errors," he writes (p. 249), "distinguishes system operators from respondents of the bulk of cultural research." Administering questionnaires to office workers may result in identifiable cultural traits, but those traits may not hold true among those who operate complex systems. Office workers do not face potentially severe consequences from error, and they rarely make immediate decisions based on their recognition of the circumstances they are encountering.

Strauch (2010) argues that to establish culture as an antecedent to error the factor must meet two initial requirements

- The factor must be strong enough to influence behavior
- The cultural trait must be sufficiently influential to affect the particular trait

In identifying national culture as an antecedent to error, investigators must have sufficient support in the literature to identify the cultural trait in question as both attributable to a particular culture and sufficiently influential to affect an operator's performance. If these criteria can be met, investigators must then meet a third criterion, excluding other potential antecedents to error. As described previously, language difficulties or training shortcomings, for example, may be incorrectly attributed to cultural factors.

In sum, the difficulty of establishing cultural factors as antecedents to error are considerable, and despite strong beliefs on an investigator's part as to their influence, the challenges to investigators in making such identifications may be formidable. Antecedents to error may well be culturally determined, but ascribing error to such factors in a way that meets the requirements of investigative logic may be difficult to achieve.

Organizational Culture

Companies, as tribes, religious groups, and nations, can influence their employee's behavior through the norms that they develop, norms that can be as powerful an influence on employee behavior as can cultural norms (e.g., Schein, 1990, 1996). Numerous illustrations of organizational practices, even among companies seemingly dedicated to enhancing operational safety, demonstrate the potentially adverse effects of norms on safety practices. For example, the *New York Times* described poor organizational practices in the National Aeronautics and Space Administration after it had experienced several major project failures, years after the 1986 accident of its Space Shuttle *Challenger*. The article reported that,

> In candid reports assessing recent problems with the National Aeronautics and Space Administration's (NASA) programs to explore Mars, two panels concluded that pressures to conform to the agency's recent credo of "faster, cheaper, better" ended up compromising ambitious projects. To meet the new constraints, the reports said, project managers sacrificed needed testing and realistic assessments of the risks of failure. (Leary, 2000)

Interestingly, the author indicated that NASA management had been criticized for many of the same management practices and norms demonstrated after the agency sustained the 1986 Space Shuttle *Challenger* accident.

As with national cultures, corporate cultural factors can affect safety, and become antecedents to error or mitigate opportunities for error. Moreover, employee groups within companies develop their own norms based on commonly held professional standards and beliefs. Vaughan (1996) examined the influence of the cultures at NASA, its primary space shuttle contractor, Morton Thiokol, and the shared engineer culture of both, on the *Challenger* accident. She suggested that engineers and their supervisors at both Morton Thiokol and NASA had developed techniques of responding to the risky technology involved in space operations that minimized the perception of and appreciation for the risks inherent to the mission. Despite considerable evidence suggesting that the low outside temperatures at the time of the launch could seriously degrade the integrity of the system, officials at both organizations agreed to the launch, which proceeded with disastrous results.

Safety Culture

Recent years have witnessed increased calls for companies to enhance their "safety cultures" as a means to improve the safety of their system operations. The term safety culture itself is largely credited to the International

Atomic Energy Agency which found that the safety culture of the Soviet Chernobyl nuclear facility created the circumstances that led to the accident. In response the International Nuclear Safety Advisory Group or INSAG, of the International Atomic Energy Agency, developed protocols for nuclear power facilities to enhance their safety culture (International Atomic Energy Agency, 1991). In the United States, two federal agencies have promulgated policies calling for the companies they regulate to implement programs to enhance their safety culture. One, the Nuclear Regulatory Commission, wrote in a policy statement:

> In the United States, incidents involving the civilian uses of radioactive materials have not been confined to a particular type of licensee or certificate holder, as they have occurred at nuclear power plants and fuel cycle facilities and during medical and industrial activities involving regulated materials. Assessments of these incidents revealed that weaknesses in the regulated entities' safety cultures were an underlying cause of the incidents or increased the severity of the incidents. (Nuclear Regulatory Commission, 2011, p. 34774)

What is safety culture and why are regulators endorsing the concept and encouraging the companies they regulate to adopt safety cultures? According to another U.S. federal agency, the Bureau of Safety and Environmental Enforcement, safety culture is defined "as the core values and behaviors of all members of an organization that reflect a commitment to conduct business in a manner that protects people and the environment" (Bureau of Safety and Environmental Enforcement, 2013).

Although the Bureau of Safety and Environmental Enforcement has defined the term, there is little uniform agreement as to what safety culture refers. This is largely because safety culture calls for the definition of two distinct terms, safety and culture, both of which are difficult to define and/or, are defined differently according to one's perspective or field of study. As a result, according to Guldenmund (2000), "the concepts of safety culture and safety climate are still ill-defined and not worked out well; there is considerable confusion about the cause, the content and the consequence of safety culture and climate, and the consequences of safety culture and climate are seldom discussed" (p. 247).

Company Practices

Aspects of a company's culture are revealed in its selection policies, operating procedures, and operational oversight, all of which can affect performance. Companies that operate complex systems are required to perform these tasks, but companies that are especially safety oriented will perform them more thoroughly, and at a higher level, than would be expected of others. Practices that encourage operator responsibility, professionalism,

and participation in safety matters can enhance operator attention to safety details; punitive practices do not. A company's culture can also be reflected in its definitions of and response to employee transgressions. Companies that require extensive documentation of occasional and infrequent medical absences, for example, encourage their employees to report to work when ill, increasing the likelihood of errors.

Managerial instability and frequent changes in supervisory personnel, supervisory practices, and operating procedures may reflect instability, an indication of a corporate cultural factor that could affect safety. Instability can adversely affect operator performance by leading to frequent changes in interpretations and enforcement of policies and procedures. One supervisor may interpret procedures literally and expect the same interpretation and compliance from operators. Another may interpret the procedures differently, and permit operators to comply with those he or she considers most important, while ignoring those that are perceived to have little or no influence on system operations. Instability can also signal dissatisfaction with the company and its practices.

Previous company incidents and accidents can also reveal much about corporate commitment to safety. Numerous incidents and accidents relative to those of comparable companies suggest deficiencies in company practices, standards, and oversight. Similar issues found in multiple events may indicate an unwillingness to identify and address potential system safety hazards. On the other hand, thorough company investigations of incidents and accidents and sincere efforts to address identified safety deficiencies reveal aspects of a positive corporate culture.

Investigators noted the adverse effects on safety of some organizational norms in a January 1996 rail accident outside of Washington, D.C. (National Transportation Safety Board, 1996). A Washington Metropolitan Area Transit Authority subway train was unable to stop and struck a train stopped ahead on the same track, killing the moving train's operator. The track had received a large amount of snow that had fallen throughout the day, reducing friction on the exposed tracks. Several times before the accident the train operator had requested authorization to disengage automatic train control and operate the train manually to better control braking on the slippery track. However, the Authority's director of operations had prohibited manual train control under any circumstances, in an effort to reduce train wheel wear. Supervisors were reluctant to violate his order and grant the train operator's request, despite their awareness of the slippery track conditions. Not one of the supervisors believed that he had the authority to countermand the policy, even though all knew that adhering to it posed a threat to system safety.

The lessons of this accident apply to others in a variety of settings. Corporate norms that encourage unquestioning acceptance of rules risk jeopardizing safety when they no longer apply, and companies that manage through fear will, over time, increase the probability of unsafe operations.

High Reliability Companies

Companies that operate complex systems can establish practices that promote safe operations. After studying high-risk systems, Rochlin (1999) described what he calls “high reliability organizations.” Expecting to focus on avoiding errors and risk management, he found that some organizations tended to anticipate and plan for, rather than react to, unexpected events. They attended to safety while efficiently operating complex systems, rewarded error reporting, and assumed responsibility for error rather than assigning fault. These companies actively sought to learn from previous errors by maintaining detailed records of past events and applying the lessons of those events to system operations. As Rochlin writes,

> Maintenance of a high degree of operational safety depends on more than a set of observable rules or procedures, externally imposed training or management skills, or easily recognized behavioural scripts. While much of what the operators do can be formally described one step at a time, a great deal of how they operate, and more important, how they operate safely, is “holistic,” in the sense that it is a property of the interactions, rituals, and myths of the social structure and beliefs of the entire organization, or at least of a large segment of it. (p. 1557)

Rochlin argues that an organization’s “interactions, rituals, and myths”—essentially its norms—can either help to create antecedents to error, or can anticipate and minimize their presence. An organization with a “good” culture encourages safety, even at the expense of production. It fosters communication among its employees and can proactively uncover problems in its operations. Westrum and Adamski (1998) offered techniques for companies to enhance safety through internal communications and error reporting.

Reason (1990) describes the benefits of programs that allow employees to report mistakes without retribution. Industries in several countries have implemented such self-reporting programs, which have provided considerable information about potential antecedents to error, before the antecedents could affect operator performance. The aviation industry has implemented a number of these programs, such as ASRS—Aviation Safety Reporting System in the United States, and CAIR—Confidential Aviation Incident Reporting, in Australia.

Organizational Cultural Antecedents and Operator Error

Identifying organizational cultural antecedents to an operator’s error calls for the same steps used to identify organizational factors as error antecedents outlined in Chapter 6. Consequently, investigators need to determine

whether the company (1) acted, decided, or made decisions improperly in the face of information alerting them to the need for different actions or decisions, (2) acted or decided improperly in the face of self-evident information of the need for corrective action, or (3) took no action or made no decision when an action and/or decision was warranted.

Summary

Cultures develop norms that influence the values, beliefs, expectations, behaviors, and perceptions of their group members. Recent studies have identified several cultural factors, including power distance, the perceived differences between superiors and subordinates, individualism–collectivism, the extent to which people accept their own goals relative to those of their group's, and uncertainty avoidance, the willingness to deal with uncertain situations, that can distinguish among members of different cultures and influence system safety. Although there is disagreement about these particular cultural factors, most researchers agree on the influence of culture on individual behaviors. However, establishing a link between cultural factors and an operator's error is difficult.

Companies also develop norms through their actions, statements, practices, and policies. Hiring criteria, training programs, operating procedures, and oversight reflect these norms. Some companies actively encourage safety by recognizing and addressing potential operational hazards. Differences between "good" and "bad" organizational cultures are suggested.

DOCUMENTING CULTURAL ANTECEDENTS

NATIONAL CULTURE

- Refer to existing research to determine the effects of norms that are believed to influence safety (e.g., Hofstede, 1980, 1991; Helmreich and Merritt, 1998; Soeters and Boer, 2000; Helmreich et al., 2001), when national cultural issues need to be examined.

ORGANIZATIONAL CULTURE

- Identify organizational cultural factors and assess their effects on system safety by interviewing employees at all pertinent company levels, and examining written documentation such as memos, organizational policies, and procedures.

- Document the extent to which company policies are enforced, and the extent to which operator expectations regarding company enforcement practices are met.
- Identify company recognized transgressions and the penalties it administers to operators who transgress.
- Evaluate the comprehensiveness of selection practices, training programs, maintenance practices, and operational oversight and, if possible, compare them to other companies in the same industry.
- Document managerial and operator turnover each year for a period of several years from the time of the event, and the reasons given for employees leaving the company.
- Determine the number of incidents and accidents the company has experienced over several years from the time of the event, assess the comprehensiveness of the organizational investigation of the events, identify common issues that may be present, and the remediation strategies the company has implemented to prevent future events.
- Document the resources that companies have devoted to programs that directly affect system safety, such as self-reporting error programs, rewards for suggestions to enhance safety, and efforts to remain current with industry and government safety programs.

References

Bureau of Safety and Environmental Enforcement. 2013. Final safety culture policy statement. *Federal Register*, 78, 27419–27421. Washington, DC: Office of the Federal Register, National Archives and Records Administration.

Carley, W. M. and Pasztor, A. 1999. Korean air confronts dismal safety record rooted in its culture. *The Wall Street Journal*, 7, A1–A2.

Chen, F. F. 2008. What happens if we compare chopsticks with forks? The impact of making inappropriate comparisons in cross-cultural research. *Journal of Personality and Social Psychology*, 95, 1005–1118.

Guldenmund, F. W. 2000. The nature of safety culture: A review of theory and research. *Safety Science*, 34, 215–257.

Heine, S. J., Lehman, D. R., Peng, K., and Greenholtz, J. 2002. What's wrong with cross-cultural comparisons of subjective Likert scales? The reference-group effect. *Journal of Personality and Social Psychology*, 82, 903–918.

Helmreich, R. L. and Merritt, A. C. 1998. *Culture at work in aviation and medicine: National organizational, and professional influences*. Aldershot, England: Ashgate.

Helmreich, R. L., Merritt, A. C., and Wilhelm, H. A. 1999. The evolution of crew resource management training in commercial aviation. *The International Journal of Aviation Psychology*, 9, 19–32.

Helmreich, R. L., Wilhelm, J. A., Klinect, J. R., and Merritt, A. C. 2001. Culture, error, and crew resource management. In E. Salas, C. A. Bowers, and E. Edens (Eds.), *Improving teamwork in organizations: Applications of resource management training* (pp. 305–331). Mahwah, NJ: Erlbaum.

Hofstede, G. 1980. *Culture's consequences: International differences in work-related values*. Beverly Hills, CA: Sage.

Hofstede, G. 1991. *Cultures and organizations: Software of the mind*. NY: McGraw-Hill.

Hofstede, G. 2002. Dimensions do not exist: A reply to Brendan McSweeney. *Human Relations*, 55, 1355–1361.

Hofstede, G. and McCrae, R. R. 2004. Personality and culture revisited: Linking traits and dimensions of culture. *Cross-Cultural Research*, 38, 52–88.

International Atomic Energy Agency. 1991. *Safety culture: A report by the International Safety Advisory Group*, Safety Series 75-INSAG-4. Vienna: International Atomic Energy Agency.

Klein, H. A. 2005. Cultural differences in cognition: Barriers in multinational collaborations. In H. Montgomery, R. Lipshitz, and B. Brehmer (Eds.), *How professionals make decisions* (pp. 243–253). Mahwah, NJ: Erlbaum.

Leary, W. E. 2000. Poor management by NASA is blamed for Mars failure. *The New York Times*, March 29, 2000.

Maurino, D. E. 1994. Crosscultural perspectives in human factors training: Lessons from the ICAO human factors program. *The International Journal of Aviation Psychology*, 4, 173–181.

McSweeney, B. 2002. Hofstede's model of national cultural differences and their consequences. *Human Relations*, 55, 89–118.

Moray, N. 2000. Culture, politics and ergonomics. *Ergonomics*, 43, 858–868.

Morris, M. W. and Peng, K. 1994. Culture and cause: American and Chinese attributions for social and physical events. *Journal of Personality and Social Psychology*, 67, 949–971.

National Transportation Safety Board. 1996. *Railroad accident report, collision of Washington Metropolitan Area Transit*. Authority Train T-111 with Standing Train at Shady Grove Passenger Station, Gaithersburg, MD January 6, 1996. Report Number: RAR-96-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1999. *Aircraft accident report, controlled flight into terrain*. Korean Air, Flight 801, Boeing 747-300, HL7468, Nimitz Hill, Guam, August 6, 1997. Report Number: AAR-99-02. Washington, DC: National Transportation Safety Board.

Nisbett, R. E., Choi, I., Peng, K., and Norenzayan, A. 2001. Culture and systems of thought: Holistic versus analytic cognition. *Psychological Review*, 108, 291–310.

Nuclear Regulatory Commission. 2011. Final safety culture policy statement. *Federal Register*, 76, 34773–34778. Washington, DC: Office of the Federal Register, National Archives and Records Administration.

Orasanu, J., Fischer, U., and Davison, J. 1997. Cross-culture barriers to effective communication in aviation. In C. S. Granrose and S. Oskamp (Eds.), *Cross-cultural work groups*. Thousand Oaks, CA: Sage Publications.

Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.

Rochlin, G. I. 1999. Safety operation as a social construct. *Ergonomics*, 42, 1549–1560.

Schein, E. H. 1990. Organizational culture. *American Psychologist*, 45, 109–119.

Schein, E. H. 1996. Culture: The missing concept in organizational studies. *Administrative Science Quarterly*, 41, 229–240.

Soeters, J. L. and Boer, P. C. 2000. Culture and flight safety in military aviation. *The International Journal of Aviation Psychology*, 10, 111–133.

Sondergaard, M. 1994. Research note: Hofstede's consequences: A study of reviews, citations and replications. *Organization Studies*, 15, 449–456.

Strauch, B. 2010. Can cultural differences lead to accidents? Team cultural differences and sociotechnical system operations. *Human Factors*, 52, 246–263.

Tayeb, M. 1994. Organizations and national culture: Methodology considered. *Organization Studies*, 15, 429–445.

Vaughan, D. 1996. *The Challenger launch decision: Risky technology, culture, and deviance at NASA*. Chicago: The University of Chicago Press.

Westrum, R. and Adamski, A. J. 1998. Organizational factors associated with safety and mission success in aviation environments. In D. J. Garland, J. A. Wise, and V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 67–104). Mahwah, NJ: Erlbaum.

9

Operator Teams

> In [the University of] Miami's pass-oriented offense, they [the offensive linemen] do this by acting as one, a solid wall, so that their individual achievement is less visible than their group achievement. The Cane's offensive line is the best such group in the country, Gonzalez says, because they are selfless and because they adjust to one another's strengths and weaknesses. They act as a unit, both on and off the field.
>
> **Jordan, 2001**
> *New York Times Magazine*

Introduction

Complex systems usually call for two or more individuals to operate equipment. The sheer complexity of these systems, the number of tasks that must be performed, and the amount of information that must be processed call for multiple operators. Further, with additional operators, should a team member commit an error, another could correct it or minimize its consequences. The use of operator teams also enables operators to share duties as needed, helping to balance individual workload as operating cycles change.

Multiple operators working together to oversee system operations form operator teams. Teams have certain characteristics, as Dyer (1984) describes,

> A team consists of (a) at least two people, who (b) are working towards a common goal/objective/mission, where (c) each person has been assigned specific roles or functions to perform, and where (d) completion of the mission requires some form of dependency among the group members. (p. 286)

This definition, applying to all teams regardless of their contexts, helps explain the common objective of operator teams in complex systems: safe and effective system operation.

Operator teams offer several advantages over single operators and an extensive body of research supports the efficacy of operator teams in complex systems. As Salas, Grossman, Hughes, and Coultas (2015) write,

> Teams are advantageous to individuals in many ways. They pool diverse knowledge and skills, allowing for convergent and divergent thinking, the building blocks of creativity and knowledge generation (Hoegl and Parboteeah, 2007). They also provide a source of backup and assistance for overworked or underskilled team members, and can be a source of positive affect and increased morale (Salas, Sims, and Burke, 2005). They allow sharing workload so that some operators do not become overwhelmed by task requirements during certain operational phases, they allow specialization among team members, so that different types of expertise can be brought to the system, enlarging the scope of expertise possible with only one operator, and they allow operators to observe the others' performance, and prevent or mitigate the effects of errors before they can lead to serious consequences.

So influential has the use of teams become in complex systems that teams have been characterized as "the strategy of choice when organizations are confronted with complex and difficult tasks" (Salas, Cooke, and Rosen, 2008, p. 540).

The value of operator teams can be seen in several accidents in which teams provided greater levels of safety than could single operators. For example, in a 1989 accident, a McDonnell Douglas DC-10 experienced a catastrophic engine failure that severed all hydraulic lines, leading to the loss of hydraulic systems and with that the loss of airplane control (National Transportation Safety Board, 1990). Fortunately, an instructor pilot who was seated in the cabin quickly recognized the severity of the problem and offered to assist the pilots. The instructor pilot had earlier practiced controlling and landing a DC-10 with a similar hydraulic failure in a flight simulator, using extraordinary and unconventional control techniques. He then guided the crew, helped manipulate the available controls, and assisted in bringing the airplane to an emergency landing. Their joint efforts saved the lives of over half the passengers and crew.

Yet operator teams, while beneficial to system safety, can also allow the introduction of unique errors into systems because of the potential for errors resulting from interactions within the teams. In such cases multiple operator teams not only do not enhance safety, they can degrade it by creating unique error antecedents. This chapter will describe elements that contribute to team effectiveness, types of team errors, and how to identify and determine the effects of the error antecedents associated with operator teams.

What Makes Effective Teams

Leadership

Effective leaders are necessary for effective teams. Burke et al. (2006a) conducted a meta-analysis of the team performance literature to determine the

type of leadership skills necessary for effective leadership. They observed that a leader "is effective to the degree that he/she ensures that all functions critical to task and team maintenance are completed" (Burke et al., 2006a, p. 289). They note that effective leaders carry this out by performing essentially two tasks: (1) overseeing team accomplishment of particular tasks and (2) facilitating team interaction and development. In their view leaders need to be both task oriented and people oriented to be effective.

Burke, Sims, Lazzara, and Salas (2007) sought to determine what makes team members follow effective leaders. They found that effective leaders engender trust among team members to enable them to follow their leadership. Among other characteristics, they suggest that trust is based upon leaders providing both compelling direction to the team so that its members perceive the tasks as challenging, clear, and consequential, and an enabling structure that facilitates the team's accomplishing the necessary tasks. Leaders are seen to genuinely care about the well-being of their subordinates and treat them fairly, manifest integrity as leaders, and provide a safe environment for their subordinates to express their views without fear of risk.

Bienefeld and Grote (2014) examined the effectiveness of leadership in a system in which multiple teams worked together within the larger system to achieve a common goal. Using a scenario based on an aircraft accident in which the pilots delayed landing after being informed of an inflight fire, they assessed how well teams of flight attendants and teams of pilots worked together, in their respective duties, to communicate the critical information pilots needed to commit to land the airplane as quickly as possible, to prepare the cabin and the passengers for the landing, and to communicate with each other to share critical information as needed. They found that "shared leadership" (p. 281), in which leaders of the respective teams led the teams in their tasks, working together toward the common goal, was a "powerful predictor" (p. 281) of the success of the teams in meeting the common goal.

Teamwork

Researchers have also focused on the role of team members, and factors that influence the extent to which they effectively work together to meet the common goal, that is, teamwork. Salas, Sims, and Burke (2005) suggest that five core components, each of which is needed for effective teamwork: team leadership, mutual performance monitoring (the extent to which team members monitor each other's performance to catch errors), backup behavior (providing resources to team members when needed), adaptability (recognizing and readjusting performance to respond appropriately to deviations), and team orientation (tendency for team members to enhance each other's performance while performing group tasks). These may be manifested differently among different teams, according to the demands on the team engendered by the particular circumstances. Teams work together through, what Salas et al. (2005) describe as three coordinating mechanisms, shared

mental models among team members of the situation being encountered and the appropriate team response, closed-loop communications in which team members effectively communicate with each other (i.e., provide and understand communications as necessary), and lastly, mutual trust.

Driskell, Goodwin, Salas, and O'Shea (2006) examined attributes that contribute to effective team member performance. Recognizing that teamwork requires skills in both performing critical system-related tasks and in interacting with team members, they studied the interpersonal skills needed for teamwork. They proposed five sets of skills that were needed to interact effectively with other team members: emotional stability, that is, lack of anxiety and being calm and self-confident; extraversion, that is, to include team orientation, social perceptiveness and expressivity, as well as the ability to subjugate desires for dominance; openness, that is, flexibility and openness to experience; agreeableness, which includes kindness, trust, and warmth; and finally conscientiousness, to include achievement striving and dependability. "We assume," they write, "…that team members who possess these personality facets will be more effective under specified conditions than those who do not" (p. 265).

Salas, Grossman, Hughes, and Coultas (2015) focused on the role of team cohesion, the extent to which team members want to work together, in team effectiveness. They found that team cohesion is a multi-dimensional trait that incorporates both the task and interpersonal elements of teamwork. They argue that cohesion is a critical element for team effectiveness.

DeChurch and Mesmer-Magnus (2010) examined the role of shared mental models in team effectiveness, defining them as "knowledge structures held by members of a team that enable them to form accurate explanations and expectations for the task, and in turn, to coordinate their actions and adapt their behavior to demands of the task and other team members" (p. 2). They found that, regardless of the measurement technique used, the research demonstrates that shared mental models among team members predict the efficacy of team performance. Burke et al. (2006b) examined the role of adaptation (or adaptability) and its role in team effectiveness. They suggest that the ability of teams to adjust their actions according to situational needs, that is, dealing with performance obstacles through innovation and adopting new routines, underlies their effectiveness in adapting to the situation, and thus in engendering team effectiveness.

Team Errors

Operators in any complex system can commit errors, but certain errors are can only be committed by operator teams. For example, Janis (1972) identified errors that teams of highly qualified individuals committed in several prominent historical events, such as the decision to invade the Bay of Pigs in

Cuba in 1961, and the failure of Admiral Husband Kimmell, the commander of U.S. forces in Pearl Harbor in 1941, to prepare for a Japanese assault.* Janis suggests that the cohesiveness of select groups and their subtle deference to respected leaders can lead to what he termed "groupthink." Groups that succumb to groupthink have difficulty considering ideas or assessing situations that are contrary to their often unspoken norms. Groupthink has since become an accepted construct in psychology, to explain certain types of group decision-making errors (e.g., Salas et al., 2005).

Teams need time to develop the necessary cohesiveness and deference to the leader that groupthink requires. However, these are not characteristic of complex systems. Although severe consequences resulted from the groupthink errors Janis cited, the environments in which the errors were committed were relatively static and the team members had sufficient time to evaluate the costs and benefits of decision options. That is not the case in complex systems where teams face time pressure, uncertainty, and potentially severe consequences from errors. The literature on team performance, which identifies factors necessary for team effectiveness, has implied that the lack of such factors contribute to team errors. Investigators need to be able to identify unique team errors and their antecedents when describing operator errors in complex systems because most such systems employ operator teams within the systems. While it may take a single engineer, for example, to operate a locomotive, it takes dispatchers working with the engineers (and conductors in some railroads) to ensure that tracks are clear, signals are correct, and that crossovers or switches are properly aligned.

DeChurch and Zaccaro (2010), as did Bienefeld and Grote (2014), looked at multi-team systems and system breakdowns. They suggest that the interdependence of different teams working together in a complex system can create difficulties that can lead to errors. As they note (p. 331), "systems fail more often because of between team breakdowns than because of within-team breakdowns," and that as teams become increasingly cohesive, the boundaries between teams may strengthen, potentially diminishing multiteam interdependence. Wilson, Salas, Priest, and Andrews (2007) studied the cause of a particular type of team error, fratricide in military environments, to develop a taxonomy of team breakdown causes. By examining one type of error, team breakdowns, they described how errors in communication, coordination, or in cooperation can lead to errors in team cognition that can lead to fratricide events.

* Since Janis completed his work, historians have reexamined Admiral Kimmel's role in the lack of effective preparations against the Pearl Harbor attack. A number believe that some in the U.S. government, while not knowing of the Pearl Harbor attack in advance, had critical intelligence of possible Japanese military strikes in the Pacific region, which they did not share with Admiral Kimmel.

Operator Team Errors

It can be seen that features of teams, team leaders, team members, and the environments in which they operate influence the likelihood of operator team errors. The roles of the operators, companies, equipment designers, and regulators, among others, in influencing operator error have previously been discussed. In this chapter errors and antecedents characteristic of teams operating complex systems will be examined.

In addition to the errors that any individual operator can commit, operator teams can in turn commit these types of errors

- Failing to notice or respond to another's errors
- Excessively relying on others
- Inappropriately influencing the actions or decisions of others, and
- Ineffectively delegating team duties and responsibilities

These errors or breakdowns in team effectiveness, which have been described previously using the terms developed by the researchers themselves, have been adopted in this text to facilitate the ability of investigator to apply the concepts from research to error investigations.

Failing to Notice or Respond to Another's Errors

The most common type of error of operator teams is committed when operators fail to notice or respond to the errors of other team members, what Salas et al. (2005) refer to as mutual performance monitoring as well as backup behavior. This error may result from any number of antecedents, such as one operator not attending to or not monitoring the actions of the other. However, in some circumstances operators notice the errors of others but fail to respond appropriately, a failure that may be due to cultural influences, as was discussed in Chapter 8. Such an error negates one of the critical advantages of the use of teams, catching or mitigating the effects of the errors of other operators.

The National Transportation Safety Board (1994) studied errors in 37 accidents that occurred in the team environment of a complex system—the cockpit of air transport aircraft. They found that one error, failing to monitor/challenge the performance/errors of another, was one of the two error types they noted that were specific to operator teams. The other, which the National Transportation Safety Board referred to as resource management, will be discussed shortly.

Excessively Relying on Others

This type of error can occur when operators possess different types or levels of expertise. It can lead to severe consequences when operators rely on other

team members to such an extent that they fail to perform their own tasks effectively.

Junior operators, who typically work alongside those with more experience, seniority, authority, or status, occasionally commit this type of error. They may disregard their own knowledge and rely excessively on others to decide, act, or perform critical duties. A team error could result if the person being relied upon makes an error, or if his or her skills or knowledge is inadequate for the task requirements. This error is highlighted in the case study of this chapter.

Inappropriately Influencing the Actions or Decisions of Others

Operators may not have sufficient time to effectively assess the situations they encounter, and in the occasionally stressful, uncertain environment that complex system operators may encounter, one operator could exert extraordinary influence on the situation awareness and subsequent actions of the others. In highly dynamic conditions an operator that assesses a situation incorrectly could adversely affect another's situation awareness, even if that person had initially assessed the situation accurately. The operator with the inaccurate situation assessment could then create an operator team error by interfering with the assessments of other team members.

A 1989 Boeing 737-400 accident illustrates how in ambiguous situations one operator can inappropriately influence the other (Air Accidents Investigation Branch, 1990). About 13 minutes after takeoff, the pilots felt what investigators termed "moderate to severe vibration and a smell of fire." The flight data recorder (FDR) showed that, at that time, the left engine was vibrating severely and exhibiting other anomalies. According to investigators,

> The commander took control of the aircraft and disengaged the autopilot. He later stated that he looked at the engine instruments but did not gain from them any clear indication of the source of the problem. He also later stated that he thought that the smoke and fumes were coming forward from the passenger cabin, which, from his appreciation of the aircraft air conditioning system, led him to suspect the No. 2 (right) engine. The first officer also said that he monitored the engine instruments and, when asked by the commander which engine was causing the trouble, he said "It's the le…It's the right one," to which the commander responded by saying "Okay, throttle it back." The first officer later said that he had no recollection of what it was he saw on the engine instruments that led him to make his assessment. The commander's instruction to throttle back was given some 19 seconds after the onset of the vibration when, according to the FDR, the No. 2 engine was operating with steady engine indications. (p. 5)

Forty-three seconds after the onset of the vibrations, the commander ordered the first officer to "shut it down," referring to the right engine.

Investigators found that, although the left engine of the two-engine airplane had sustained substantial internal damage, damage that had caused the vibrations that the pilots observed, they incorrectly shut down the right engine in the mistaken belief that it was the one that was causing the difficulties. That engine was later found to have been undamaged before the accident. Rather, the left engine, the one pilots believed to have been operating effectively, was found to have been damaged. The pilots recognized this only moments before the accident, when it was too late to restart the right engine and avoid the impact. The aircraft crashed short of the runway, striking a motorway. Although no one on the ground was injured, 47 passengers were killed and 74 passengers and crew were seriously injured in the accident. It is possible, if not likely, that had the first officer said nothing, with the captain's experience, he would have correctly identified and responded correctly to the engine that had failed.

Failing to Delegate Team Duties and Responsibilities

Operators must attend to ongoing system operations when responding to emergencies. These can create considerable demands on their attention, and can lead to errors in either the emergency response or in system operations. In situations such as these operator teams can effectively respond to the different operational requirements, responding to the emergency and managing system operations, provided team leaders delegate responsibility to operators to both operate the system and respond to the anomaly in these situations. Failing to delegate tasks to team members in nonroutine situations can lead to a team error as the response to either the anomaly, or the system operation, or both, may be erroneous.

A team of three pilots committed this type of error in a 1972 accident involving a Lockheed L-1011 that crashed in the Florida Everglades, a vast national park in South Florida (National Transportation Safety Board, 1973). The three had put the airplane into a hold over the Everglades while they attempted to determine the cause of an indicator failure. The indicator, which had failed to illuminate, signified the status of the landing gear, whether extended or retracted. The three pilots attended to the indicator light but not to the airplane's flight path and as a result they did not notice that the mechanism that controlled the airplane's altitude had disengaged. The airplane slowly lost altitude until it struck the ground.

Researchers at the National Aeronautics and Space Administration, later studied this type of error. Using a Boeing 747 flight simulator they examined the response of pilots to a system anomaly (Ruffell-Smith, 1979). Using actors as cabin crewmembers they presented pilots with a scenario that included an anomaly, and then tried to distract the pilots with nonessential questions from the "cabin crewmembers." Several pilots responded to the "cabin crewmembers," became distracted, and committed errors that exacerbated the severity of the situation. As in the Everglades accident, the pilots in the

simulator allowed an anomaly to become a serious event by failing to ensure that team members were monitoring the system, and by not ignoring noncritical distracters to enable them to focus on more critical tasks during the high workload periods being observed.

In response to these findings, and to those of several accident investigations, airlines and the research community developed crew resource management (or CRM) to help crewmembers contribute effectively to both routine and nonroutine system operations. The programs stressed the need for clear, unambiguous delineation and assignment of operator duties and responsibilities in response to nonroutine situations (e.g., Foushee and Helmreich, 1988; Helmreich and Foushee, 1993; Helmreich and Merritt, 1998). Today, CRM is widely accepted in aviation, marine, and rail operations, and other systems where operator teams are used to control the systems. It has evolved to where it no longer merely strives to improve team performance in general but to enhance operator teams' abilities to mitigate error. As Salas, Burke, Bowers, and Wilson (2001) write, CRM

> represents an awareness that human error is inevitable and can provide a great deal of information. CRM is now being used as a way to try to manage these (human) errors by focusing on training teamwork skills that will promote (a) error avoidance, (b) early detection of errors, and (c) minimization of consequences resulting from CRM errors. (p. 642)

Unfortunately, the research findings on the safety effects of CRM have not been consistent. Helmreich, Merritt, and Wilhelm (1999), in observing actual flights, found that CRM training improved the quality of crew performance. However, reviews of the efficacy of CRM programs have been uncertain. Salas et al. (2001), Salas, Wilson, Burke, and Wightman (2006), and O'Connor et al. (2008), respectively, conducted mega-analyses of research on CRM to determine the consensus of research on the efficacy of CRM. The findings of each study were consistent in that CRM training changed operator attitudes regarding teamwork and team effectiveness. However, with regard to changing behaviors and to improving safety, the results were mixed.

Operator Team: Antecedents to Error

Antecedents that lead to individual operator errors can also lead to team errors. In addition, antecedents unique to operator teams can lead to team errors. Antecedents to individual operator errors can harm team effectiveness by degrading the performance of a member of an operator team, thereby leading to team errors. Antecedents that degrade team performance are unique to multiple operators, but the effects may be the same in terms of their adverse influence on team effectiveness.

Equipment

As discussed in Chapter 4, features of information presentation and control design affect operator performance. Those that apply to single-operator systems apply to operator teams as well, with some additions. These pertain to an operator's ability to (1) interact with other team members, (2) access the information presented to other team members, and (3) control the system for other team members.

Equipment designed for multiple operators enables team members to communicate with each other when needed, access critical information, and maintain system control. However, design features of some systems may interfere with team performance (e.g., Bowers, Oser, Salas, and Cannon-Bowers, 1996; Paris, Salas, and Cannon-Bowers, 2000). For example, some designs prevent operators from learning of other team members' control inputs and the system information they receive. Actions on keyboards or touchscreens, for example, are not as salient to other team members as are lever movements. Replacing levers with touchscreens can decrease the ability of team members to learn of their colleagues' control inputs, thereby degrading both individual and team situation awareness.

Operator

Physiological and behavioral antecedents that lead to errors in single-operator systems can affect operator teams as well. The influence of these antecedents on operator performance in single operator or operator team systems is comparable.

Company

Companies have substantial influence on the quality of the teams they employ, as discussed in Chapter 6. Companies evaluate candidates' interpersonal skills, in addition to their technical expertise, when selecting candidates for operator team positions. Those who are unable to interact effectively with other team members can adversely affect the quality of their team's performance and companies should screen applicants to assure that those it hires can interact effectively with team members.

Foushee (1984) described an incident on an air transport aircraft in which a captain demeaned a first officer and expressly discouraged him from providing input to the conduct of the flight. The captain's actions degraded the quality of team interactions by belittling a team member and thus discouraging him from contributing to team effectiveness. Because of the captain's behavior, the first officer was less likely to speak up in response to an error of the captain, or even may have been unwilling to mitigate the effects of that error. Since then operators in many cultures have developed little tolerance

for such actions by individuals in positions of responsibility in safety-critical systems. Their behavior reflects on the company's selection criteria, training, and oversight as much as on them as individuals.

The quality of a company's procedures can also affect the quality of team member interaction and serve as an antecedent to operator team errors. For example, companies can require operators to challenge and respond to each other, so that one verifies that another has performed a task, or one confirms that he or she received information from the other. Procedures can increase the level of operator contribution to team tasks, encourage operators to observe and participate in aspects of each other's performance, and reduce antecedents to error among team members.

Number of Operators

The number of operators performing a given task can influence the quality of the task. An excessive number can degrade communications within a group and lower individual workload to the point that operators become bored, adversely affecting system monitoring and other aspects of performance (O'Hanlon, 1981). However, because of financial concerns, most organizations are more likely to have too few rather than too many operators, and as a result, this will not be considered further.

Situations in which the available number of operators is insufficient for the tasks to be performed occasionally occur, especially during nonroutine situations. An insufficient number of operators can increase operator workload, increase individual team member stress, and reduce levels of operational safety (Paris et al., 2000).

Yet, the dynamic nature of complex systems can make it difficult to plan for a constant workload. Operating cycles, with differing operator workload requirements, need different numbers of operators. A team that has a sufficient number of operators for one operating phase may have an insufficient number for another, and a team that is insufficient for nonroutine operations may be excessive for routine conditions. The adequacy of the number of operators assigned to a task will vary according to the operating phase, its complexity, and the level of operator workload.

Team Structure

Operators in teams work best when each team member understands his or her tasks, and contributes to the work of the other team members without interfering with their tasks (Paris, Salas, and Cannon-Bowers, 1999). Teams in which members are uncertain of their roles and responsibilities are said to have poor structures. However, as with team size, a team structure that is effective for routine operations may be ineffective for nonroutine situations. As seen in the 1972 accident involving the Lockheed L-1011 that crashed

in the Florida Everglades, a team structure effective for routine operations could break down in nonroutine circumstances. Despite their response to what turned out to have been a relatively benign situation, a visual alert that did not illuminate as expected, the team members failed to monitor a critical element of system operations, the airplane's altitude.

Some have found that operators' roles within their teams can affect their situation awareness and other critical performance elements. For example, in commercial aviation one pilot typically performs the flying duties and the other monitors the subsystem performance and supports the "flying" pilot, although the captain remains in command throughout. On subsequent flights they generally alternate duties as pilot flying and pilot not flying. Jentsch, Barnett, Bowers, and Salas (1999) reviewed over 400 anonymous reports that pilots had filed describing their own errors to an anonymous self-reporting system. They found that captains were more likely to lose situation awareness when they were flying the airplane, that is, actively engaged in system control, and when the subordinate pilots, the first officers, were monitoring the captains' performance. Captains were less likely to lose situation awareness when the first officers were performing the flying duties and they were monitoring the others' performance. The findings contradict a common belief that active engagement in system control enhances situation assessment. The researchers suggest that monitoring gave the captains the ability to observe system parameters and obtain situation awareness better than would have been true had they been flying the aircraft themselves. In addition, the superior–subordinate positions of captains and first officers, which made the latter somewhat reluctant to alert the captains to their errors when they were the flying pilots, may have also contributed to the captains' reduced situation awareness when they were flying.

Team Stability

Team stability, the extent to which team members remain together as a working team, can also affect the quality of team performance. Working together allows team members to learn about each other's performance and work styles, and to develop reasonably accurate expectations of other's near-term performance, as often occurs with members of athletic teams who have played together over a period of time. The players and the team members learn subtle aspects of each other's performance over time that enable them to reliably predict each other's actions, facilitating communications and enhancing performance. In emergency operations, when operators may face intense workload and have little available time, stability can lead to enhanced communications as the operators accurately anticipate each other's actions without articulating them.

However, in some systems long-term stability may not be possible. Contractual obligations and prevailing customs may dictate different

work schedules among team members with different levels of seniority. Several airlines, for example, employ thousands of pilots, many of whom fly with pilots they had neither flown with nor even met previously. In systems such as these, the consistent application of standard operating procedures can compensate for the lack of team stability. Well-defined and practiced procedures enable operators to anticipate their fellow operators' actions in each operating phase, during both routine and nonroutine situations, regardless of the length of time they had been teamed with the other operators.

Companies can also use operator selection to counteract the potentially adverse effects of team instability. Paris et al. (2000) suggest that the most critical determinant of the effects of instability on team performance is the skill level of the operator leaving the team. "As a general rule," they note, "there is little disruption of team performance from turnover, as long as only one team member is replaced at a time and that replacement is as skilled as the person he replaced" (p. 1060).

Leadership Quality

Leadership has been discussed previously in this chapter. Team leader quality can affect team performance quality, particularly during critical situations. The research is consistent in that team leaders in complex systems contribute to the climate in which the group operates, whether autocratic, democratic, or something in between. Leaders implement rewards and punishments, and assign tasks. In these and other daily interactions, leadership quality affects team performance quality. Military organizations, where adherence to a superior's orders is required, recognize that effective leaders elicit superior team member performance rather than compel it. As a result, leaders are encouraged to obtain voluntary cooperation from their subordinates rather than demand what can become reluctant or grudging cooperation.

In commercial aviation early CRM programs addressed leadership quality as a critical element for successful interaction between superior and subordinate pilots. Good leaders attend to both operating tasks and subordinate concerns. Later CRM programs addressed additional elements of team performance and broadened the scope of team membership to include other operators in the system.

Cultural Factors

Cultural factors and their effects on system performance are discussed extensively in Chapter 8. Suffice to say that different cultures respect and defer to leaders, rules, procedures, and teams differently, and their values can affect the quality of operating team performance.

Case Study

The relationship of operator team antecedents to errors can been seen in the collision of two commercial aircraft, a McDonnell Douglas DC-9 and a Boeing 727, in heavy fog at Detroit Metropolitan Airport in December 1990 (National Transportation Safety Board, 1991). The DC-9 was destroyed and eight of the 44 people onboard were killed in the accident, although no one on the Boeing 727 was injured. During severely limited visual conditions, the DC-9 pilots mistakenly taxied their aircraft onto an active runway and into the path of the Boeing 727 as it was taking off. The Boeing 727 pilots were unable to see the DC-9 in time to prevent the collision.

Heavy fog places substantial burdens on both pilots and controllers at airports that lack ground radar, as was the case at the Detroit airport at the time of the accident. If visibility is sufficiently limited, pilots are unable to see beyond a short distance in front of their airplanes, and they would be prohibited from taking off or landing. Conditions at the time of this accident approached, but did not exceed the visibility limits, but Detroit air traffic controllers were unable to see taxiing aircraft from the control tower, and pilots had difficulty establishing their positions at the airport. In these conditions—when planes could still operate but visibility is quite limited—both controllers and pilots rely on each other for airplane location information. Controllers depend on the pilots to inform them of their positions at the airport, and pilots depend on the controllers to separate them from other aircraft.

The limited visibility added to the workload of both pilots and controllers. Controllers were unable to verify airplane positions and pilots lacked many of the visual cues needed to verify their positions on the airport. Markings that had been painted on runways and taxiways and served as guides to pilots were also not visible because a thin layer of snow had obscured them.

The operator team on the DC-9 consisted of two pilots, a captain, the superior, who was making his first unsupervised air transport flight after a 6-year hiatus, following his recovery from a medical condition that was unrelated to his aviation duties, and a subordinate, the first officer. In the 6-year interval between medical disqualification and his return to flying, the airline ownership had changed, and the airline that had employed him had been purchased by another airline. When he returned to flying the captain had to not only requalify to operate the DC-9 but learn his new employer's operating procedures as well.

The DC-9 first officer had retired from the U.S. Air Force, where he had been a pilot in command of large bomber aircraft. At the time of the accident he was within his probationary first year period with the airline. The airline's personnel rules allowed it to terminate the employment of pilots in their probationary periods without cause. In the 6 months since he joined the airline, he had flown into and out of Detroit 22 times, only one or two of them, according to his estimates, were in restricted visibility conditions.

Cockpit voice recorder data revealed that the first officer exaggerated attributes of his background to the captain. Unsolicited, he told the captain that he had retired from the air force at a rank that was higher than the rank that he had actually attained. He claimed to have experienced an event when flying combat operations, before joining the airline, that he had not experienced. During the taxi from the gate he committed several errors, while ostensibly assisting the captain. Even when uncertain in the restricted visibility that was prevailing, he unhesitatingly gave their location to the captain, even though he was not certain of all the locations, and he continued to do so after misdirecting the captain on the airport surface, thereby requiring the air traffic controllers to give them a new taxi clearance to the active runway.

Although in this type of airplane captains steer the airplane while taxiing, both pilots work together using airport charts and external visual information to verify that the taxi route they follow corresponds to the assigned route. Both also simultaneously monitor air traffic control communications for pertinent information, and they monitor the aircraft state.

Early in their taxi the first officer told the captain, "Guess we turn left here." The captain responded, "Left turn or right turn"? The first officer answered by describing what he believed to be their position. The captain then answered, "So a left turn," and the first officer agreed. Ten seconds later he directed the captain, "Go that way" and the captain complied. This type of exchange between the captain and first officer continued for about 2 minutes, until the first officer, in response to an air traffic controller's question about their location answered, "Okay, I think we might have missed oscar six," the name of the taxiway to which they had been assigned. By misdirecting the captain to a wrong turn on the airport he had endangered the safety of the flight, but neither pilot had apparently recognized the significance of that error.

Yet, even after being misdirected, the captain continued to accept the first officer's guidance. For the next 5 minutes the captain continued to ask the first officer, "What's he want us to do here," "This a right turn here Jim," and "When I cross this [runway] which way do I go, right"? and other similar questions. The first officer continued to direct the captain until they crossed onto the active runway and encroached upon the path of the departing Boeing 727. By the time of the accident, the first officer had provided all taxi instructions to the captain, which the captain followed without hesitation.

The captain made a key operator team error by over-relying on the first officer. His error is understandable given his return to active flying after the long hiatus, and his likely belief in the first officer's superior airport knowledge gained from more recent experience operating at Detroit. The first officer's seeming confidence in his knowledge of the airport routing appears to have exacerbated the captain's preexisting tendency to rely on him while navigating on the Detroit airport surface. The interaction of an overly assertive subordinate, with a tendency to exaggerate his accomplishments and knowledge, albeit a tendency the captain could not have been aware of, and a superior relatively inexperienced in the circumstances that existed at the

time, combined to create unique operator team errors. Had the captain relied less on the first officer and been more attentive to information on their airport position, the accident may have been avoided.

Summary

Complex systems often require operator teams, two or more operators working toward a common goal or objective. They can enhance team performance by helping to prevent errors and mitigate the effects of errors that have been committed. Multiple operators can reduce individual workload, and assure that necessary tasks are performed during nonroutine or emergency situations. Teams depend upon the effective work of each team member and good leadership qualities of the team leader.

Operator teams in complex systems can also commit errors unique to teams. These include failing to notice or to respond to another's error, relying excessively on others, incorrectly influencing the situation assessment of others, and failing to ensure that duties and responsibilities are delegated. Antecedents to these errors may lie within the culture or the company, or result from other factors specific to operator systems.

Antecedents of error in both single-operator and operator team systems include those discussed in previous chapters, such as equipment design, operator factors, company and regulator factors, as well as several that are specific to operator teams. These include the shortcomings in the number of operators for the task, team structure, team stability, leadership quality, and cultural factors that can degrade team performance.

DOCUMENTING ANTECEDENTS TO OPERATOR TEAM ERRORS

GENERAL

- Determine the critical errors that are believed to have led to the event and identify the team members who likely committed those errors.
- Determine the number of tasks that operators attempted to perform, the amount of time available to perform those tasks, and the actions and decisions of each team member by interviewing operators, examining recorded data, and referring to operating manuals and other documents.
- Document pertinent antecedents to single-operator type errors (such as those resulting from performance or procedural

deficiencies, discussed in previous chapters) and examine potentially relevant equipment, operator, and company factors if the error appears to be an operator type error.

OPERATOR TEAM ANTECEDENTS

- Document the number of operators called for and the number of operators involved in system operation at the time of the event.
- Assess the adequacy of the number of operators available to perform the tasks in the allotted time.
- Identify the duties of each team member and determine the extent to which each team member understood his or her duties, and performed them.
- Determine the length of time that the team members had worked together as a team.
- Describe communications among the team members, and supervisor/subordinate communications.
- Examine the ease with which the equipment used enabled team members to recognize and become aware of the information received by their fellow team members and their actions with regard to the system.
- Document company training, guidelines, and procedures that relate to team performance, and assess the extent to which these encourage team integration and team performance.
- Assess the proportion of training, guidelines, and procedures devoted to team performance and the extent to which they call for team, as opposed to individual, operator tasks.
- Document interpersonal skills of operator applicants and leadership skills of supervisor applicants by examining company selection criteria and history, and interviewing supervisors, subordinates, and colleagues.
- Assess the extent to which the training, guidelines, and procedures pertain to team structure, team member responsibilities, and leadership qualities.

References

Air Accidents Investigation Branch. 1990. *Report on the accident to Boeing 737-400, G-OBME, near Kegworth, Leicestershire, January 8, 1989*. London: Department of Transport.

Bienefeld, N. and Grote, G. 2014. Shared leadership in multiteam systems: How cockpit and cabin crews lead each other to safety. *Human Factors*, 56, 270–286.

Bowers, C. A., Oser, R. L., Salas, E., and Cannon-Bowers, J. A. 1996. Team performance in automated systems. In R. Parasuraman and M. Mouloua (Eds.), Automation and human performance: Theory and applications (pp. 243–263). Mahwah, NJ: Erlbaum.

Burke, C. S., Sims, D. E., Lazzara, E. H., and Salas, E. 2007. Trust in leadership: A multi-level review and integration. *The Leadership Quarterly*, 18, 606–632.

Burke, C. S., Stagl, K. C., Klein, C., Goodwin, G. F., Salas, E., and Halpin, S. M. 2006a. What type of leadership behaviors are functional in teams? A meta-analysis. *The Leadership Quarterly*, 17, 288–307.

Burke, C. S., Stagl, K. C., Salas, E., Pierce, L., and Kendall, D. 2006b. Understanding team adaptation: A conceptual analysis and model. *Journal of Applied Psychology*, 91, 1189–1207.

DeChurch, L. A. and Mesmer-Magnus, J. R. 2010. Measuring shared team mental models: A meta-analysis. *Group Dynamics: Theory, Research, and Practice*, 14, 1–14.

DeChurch, L. A. and Zaccaro, S. J. 2010. Perspective: Teams won't solve this problem. *Human Factors*, 52, 329–334.

Driskell, J. E., Goodwin, G. F., Salas, E., and O'Shea, P. G. 2006. What makes a good team player? Personality and team effectiveness. *Group Dynamics: Theory, Research, and Practice*, 10, 249–271.

Dyer, J. L. 1984. Team research and team training: A state-of-the-art review. In F. A. Muckler (Ed.), *Human factors review*. (pp. 285–323). Santa Monica, CA: Human Factors Society.

Foushee, H. C. 1984. Dyads and triads at 35,000 feet. *American Psychologist*, 39, 885–893.

Foushee, H. C. and Helmreich, R. L. 1988. Group interaction and flight crew performance. In E. L. Wiener and D. C. Nagel (Eds.), *Human factors in aviation* (pp. 189–227). San Diego, CA: Academic Press.

Helmreich, R. L. and Foushee, H. C. 1993. Why crew resource management: Empirical and theoretical bases of human factors training in aviation. In E. Wiener, B. Kanki and R. Helmreich (Eds.), *Cockpit resource management* (pp. 1–45). San Diego, CA: Academic Press.

Helmreich, R. L. and Merritt, A. C. 1998. *Culture at work in aviation and medicine: National organizational, and professional influences*. Aldershot, England: Ashgate.

Helmreich R. L. Merritt, A. C., and Wilhelm, H. A. 1999. The evolution of crew resource management training in commercial aviation. *The International Journal of Aviation Psychology*, 9, 19–32.

Janis, I. L. 1972. *Victims of groupthink.* Boston, MA: Houghton Mifflin.

Jentsch, F., Barnett, J., Bowers, C. A., and Salas, E. 1999. Who is flying this plane anyway? What mishaps tell us about crew member role assignment and air crew situation awareness. *Human Factors*, 41, 1–14.

Jordan, P. 2001. This line will not be crossed. *The New York Times Magazine*, December 23.

National Transportation Safety Board. 1973. *Aircraft accident report, Eastern Air Lines, Inc., L-1011, N310EA, Miami, Florida, December 29, 1972*. Report Number: AAR-73-14. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1990. *Aircraft accident report, United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989*. Report Number: AAR-90-06. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1991. *Aircraft accident report, Northwest Airlines, Inc., Flights 1482 and 299, runway incursion and collision, Detroit Metropolitan/Wayne County Airport, Romulus, Michigan, December 3, 1990*. Report Number: AAR-91-05. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1994. *Special study, a review of flightcrew-involved, major accidents of U.S. air carriers, 1978 through 1990*. Report Number: SS-94-01. Washington, DC: National Transportation Safety Board.

O'Connor, P., Campbell, J., Newon, J., Melton, J., Salas, E., and Wilson, K. A. 2008. Crew resource management training effectiveness: A meta-analysis and some critical needs. *The International Journal of Aviation Psychology*, 18, 353–368.

O'Hanlon, J. F. 1981. Boredom: Practical consequences and a theory. *Acta Psychologica*, 49, 53–82.

Paris, C. R., Salas, E., and Cannon-Bowers, J. A. 1999. Human performance in operator systems. In P. A. Hancock (Ed.), *Human performance and ergonomics* (pp. 329–386). San Diego, CA: Academic Press.

Paris, C. R., Salas, E., and Cannon-Bowers, J. A. 2000. Teamwork in multi-person systems: A review and analysis. *Ergonomics*, 43, 1052–1075.

Ruffell-Smith, H. P. 1979. *A simulator study of the interaction of pilot workload with errors, vigilance, and decisions*. (NASA Technical Memorandum 78482). Moffett Field, CA: NASA-Ames Research Center.

Salas, E., Burke, C. S., Bowers, C. A., and Wilson, K. A. 2001. Team training in the skies: Does crew resource management (CRM) training work? *Human Factors*, 43, 641–674.

Salas, E., Cooke, N. J., and Rosen, M. A. 2008. On teams, teamwork, and team performance: Discoveries and developments. *Human Factors*, 50, 540–547.

Salas, E., Grossman, R., Hughes, A. M., and Coultas, C. W. 2015. Measuring team cohesion: Observations from the science. *Human Factors*, 57, 365–374.

Salas, E., Sims, D. E., and Burke, C. S. 2005. Is there a "big five" in teamwork? *Small Group Research*, 36, 555–599.

Salas, E., Wilson, K. A., Burke, C. S., and Wightman, D. C. 2006. Does crew resource management training work? An update, an extension, and some critical needs. *Human Factors*, 48, 392–412.

Wilson, K. A., Salas, E., Priest, H. A., and Andrews, D. 2007. Errors in the heat of battle: Taking a closer look at shared cognition breakdowns through teamwork. *Human Factors*, 49, 243–256.

Section III

Sources of Data

10

Electronic Data

> The telltale recorder, known as a Sensing and Diagnostic Module or S.D.M., was one of six million quietly put into various models of General Motors [G.M.] cars since 1990. A newly developed model being installed in hundreds of thousands of G.M. cars this year records not only the force of collisions and the air bag's performance, but also captures five seconds of data before impact. It can determine, for example, whether the driver applied the brakes in the fifth second, third second or last second. It also records the last five seconds of vehicle speed, engine speed, gas pedal position and whether the driver was wearing a seat belt.
>
> **Wald, 1999**
> *New York Times*

Devices that record system parameters are found in many complex systems, providing valuable investigative data. Traditionally associated with commercial aircraft, these devices are increasingly found in other systems, including railroad locomotives, marine vessels, and, as noted, automobiles.

Types of Recorders

In general, two types of devices have been used to capture data in complex systems, audio/video recorders and system-state recorders, although on occasion devices intended for other purposes may provide helpful information as well. Security cameras, for example, which are proliferating across many domains as their cost declines, can provide valuable data to both accident investigators and criminal investigators. More recently, the decreasing cost of capturing and recording video data has enabled many companies who would otherwise not have done so to place video recorders in operator consoles to capture images of operators during system operations. Each device, whether a camera or direct system recorder, collects information that could give investigators insight into the state of the operating system, its components and subsystems, the operating environment, as well as operator actions.

Audio/Video Recorders

Because of their prominence in aircraft accident investigations, cockpit voice recorders, often referred to as "black boxes," are among the most well-known recorders that investigators use. These record aircraft cockpit sounds in a flight's last 2 hours of operation.

Audio recorders are also found in other systems. Air traffic control facilities record communication between pilots and controllers, and electronically transmitted voice communications among controllers. Marine vessel traffic centers capture communications between vessel operators and ground station personnel, and railroad control facilities record voice communications between dispatchers and train crews.

Video recorders are not extensively used in complex systems at present, primarily because of both technical and legal reasons. Until recently, the costs of rewiring systems to employ video recorders and store the recorded data were prohibitive, and the size of recording equipment interfered with system operations. However, technical improvements have lessened the scope of these shortcomings and video records of system operations are becoming increasingly available to investigators.

The use of video recorders in accident investigations has also raised legal issues that have limited their use (Fenwick, 1999). Concerns such as operator privacy, post-event litigation, and unauthorized release of video data have yet to be resolved, and many potential users are reluctant to use them until these issues are resolved to their satisfaction. However, many investigators have called for the installation and use of video recorders to enhance safety (e.g., National Transportation Safety Board, 2000). As these calls increase and as technical advances continue, video recorder use in complex systems will almost certainly increase. Video recordings, whether still or motion, can provide critical information on the actions of the operator before the accident. Investigators can use this information to determine how closely those actions matched other information about the accident, and whether the operator performed as appropriate for the particular circumstances at the time.

System-State Recorders

System-state recorders are found in many systems. In air transport aircraft they continuously record several hundred flight parameters over a 25-hour period. The International Maritime Organization has required internationally operating marine vessels to be equipped with voyage data recorders, devices that record the ship's position, speed, heading, echo sounder, main alarms, rudder order and response, hull stresses, and wind speed and direction, for 12 continuous hours (Brown, 1999). The U.S. Federal Railroad Administration requires trains that can exceed 30 miles per hour be equipped with event recorders that record speed, direction, time, distance, throttle position, brake application, and, in some cases cab signals, for 48 continuous hours (Dobranetski and Case, 1999).

The value of the data that system recorders capture was evident in the investigation of a 1997 passenger train derailment. The accident occurred after a flash flood had weakened the underlying support of a bridge that the train was traversing (National Transportation Safety Board, 1998a). According to investigators,

> All four locomotive units were equipped with GE Integrated Function computer event recorders…The data from the lead locomotive indicate that the train was traveling approximately 89 to 90 mph, with the throttle in position 3 (with a change to 4 and then 1), when the brake pipe pressure decreased from approximately 110 to 0 psi, and the emergency parameter changed from NONE to TLEM [Train Line Induced Emergency]. Within the next 2 seconds, the pneumatic control switch (PCS) parameter changed from CLOSED to OPEN. Between 2 and 4 seconds after the PCS OPEN indication, the position of the air brake handle changed from RELEASED to EMERGENCY, and the EIE [Engineer Induced Emergency] parameter changed from OFF to ON. (p. 39)

Investigators recognized from these data that the emergency brakes had been applied before the derailment, information that was critical to understanding the engineer's performance. Thus the engineer had attempted to stop the train before the derailment, but was unable to do so in time.

Recorders need not necessarily be physically located within a system to capture data. For example, large airports are equipped with detectors that record weather data such as ceiling level, visibility, wind direction and velocity, barometric setting, and precipitation amount and duration. Some electrical generating facility smokestacks are equipped with detectors that measure and record wind direction and velocity, and some bridges have the ability to capture and record the water levels underneath them.

Other Electronic Data

Investigators can often obtain recorded data from a variety of sources, some of which may have been implemented for purposes other than accident investigation. For example, government agencies, companies, and individuals place security cameras in and around buildings, equipment, yards, and other facilities, equipment that could provide information on the actions of critical people, as well as changes in lighting, weather, and equipment condition. Computers, smart phones or other data storage devices that operators, supervisors, and others use may also contain valuable data.

The value of data from these recorders that were not part of the system was apparent in the investigation of a September 1989 accident involving a DHC-6, an airplane that was not equipped with recorders at the time (National Transportation Safety Board, 1991). Eight passengers and the two pilots were killed in the accident. Investigators obtained a video recording from a passenger video camera used during the flight. Because there was

no barrier between the airplane's cockpit and the cabin, passengers had an unobstructed view of the pilots. The video showed the pilots' arm and hand movements during the accident sequence, information that demonstrated that they had difficulty controlling the airplane during the landing, and had attempted to stop the landing to try again. However, in attempting to reject the landing each pilot tried to operate the same controls at the same time. Their arm motions interfered with each other's actions, and they rapidly lost control of the airplane. The information was invaluable; without it investigators would have had substantial difficulty determining the accident's cause.

Investigators of a marine accident made a particularly innovative use of security camera recordings to determine the angle at which the vessel heeled, or turned on its longitudinal axis, during a turn after the operator mistakenly turned the vessel in a series of increasingly greater turns to counter what had initially been mildly excessive steering commands by the vessel's integrated navigation system (National Transportation Safety Board, 2008). Because of limitations in the instrumentation used to measure and record certain data, the vessel's voyage data recorder showed the vessel heeling to 15°, the maximum angle the recorder would read. By contrast evidence from passenger injuries and damage to objects throughout the vessel suggested a greater heeling angle. Video cameras, for example, recorded passengers being thrown out of the pool as the pool water moved in increasingly greater motion, consistent with increasing heel angles.

As can be seen in Figure 10.1, by noting the time stamped onto the image of a security camera that captured part of the external side of the vessel, and noting the sun's angle on the horizon in the photo, and measuring the difference between the "angle of the shadow created by the vessel on a reference point on the images and the angle that would have been created by the ship's

FIGURE 10.1
External security camera photograph of *Crown Princess* used to determine vessel heel angle. (Courtesy of the National Transportation Safety Board.)

orientation to the sun at that time, given the sun's angle over the horizon and the ship's orientation" (p. 20), investigators determined that the actual heeling angle was 24°, an angle well-beyond what cruise vessel passengers could reasonably expect to encounter on a vacation cruise. By using data from a security camera, investigators were able to determine the actual vessel heeling angle more accurately than was measured by the instrument installed on the vessel to do so. As they described in the text accompanying Figure 10.1,

> Image of the *Crown Princess* taken by a ship's video camera at the maximum angle of heel, with reference lines added by investigators. Stamped time corresponds to 1525:02 eastern daylight time. The apparent bending of the horizon is an artifact of the wide-angle camera lens, which causes straight lines to appear curved and bow outward from the image center. (p. 21)

System Recorder Information

Audio Recorders

Audio recorders can provide real-time information on both the operator and the equipment.

The operator. Audio recordings reveal operators' verbal interactions in operator teams. For example, in airline operations pilots perform procedures in strict order, established on checklists that are specific to the different operating phases. Generally, one pilot identifies the checklist item and the other performs and articulates the action taken in response, or describes the status of a particular component. Recordings of pilot statements or comments can help investigators determine whether they completed the required tasks, and the sequence in which they performed the tasks.

This information was particularly helpful in the investigation of an August 1987 MD-80 accident in Detroit, Michigan (National Transportation Safety Board, 1988). The pilots were following the checklist while they taxied the airplane from the terminal to the runway. The checklist included a step that called for one pilot to extend the flaps and slats for takeoff, and the other pilot to verify that this had been accomplished, a critical action because taking off with the flaps and slats retracted jeopardize the safety of flight.

Audio recorder data revealed that the pilots' checklist review was interrupted when an air traffic controller requested information from them. The pilots responded to the controller and resumed the checklist tasks but at the wrong checklist location, inadvertently omitting several required steps, including verifying the flap and slat extension. They attempted to takeoff but the airplane was unable to climb. It crashed shortly after the start of the takeoff, killing all but one of the more than 150 passengers and crew onboard. Cockpit voice recorder data enabled investigators to learn not only

the nature of the operators' error, but the context in which they committed the error as well, giving investigators a fairly comprehensive perspective on the pilots' error.

Audio recorder information can also complement other operator-related data. For example, after an extensive inquiry, investigators of a September 1994 accident involving a Boeing 737 that crashed near Pittsburgh, Pennsylvania, determined that the rudder had abruptly moved to one side just before the accident (National Transportation Safety Board, 1999). This caused the airplane to turn left and dive abruptly to the ground. Investigators had to determine whether the airplane's turn had been initiated by pilot action or by the rudder itself, because the flight recorder data showed the turn but not its source.

Investigators used different techniques to understand the cause of the turn. They analyzed sounds that the pilots made during the accident sequence and compared them to the sounds that they had made during routine portions of the flight. By examining elements of pilot sounds, including voice pitch, amplitude, speaking rate, and breathing patterns, investigators determined that,

> The first officer emitted straining and grunting sounds early in the upset period, which speech and communication experts stated were consistent with applying substantial physical loads; the CVR [cockpit voice recorder] did not record any such sounds on the captain's microphone channel until just before ground impact. After about 1903:18 (about 5 seconds before ground impact) … the captain's breathing and speed patterns recorded by the CVR indicated that he might have been exerting strong force on the controls. (pp. 247–248)

These sounds, with other information, convinced investigators that the pilots did not initiate the turn and subsequent dive. The straining and grunting sounds heard on the recording were characteristic of those made during utmost physical exertion. Pilots would make these sounds when forcefully attempting to counteract a maneuver, not when initiating one that would have taken little physical effort.

Audio recorder data can also reveal operators' perceptions of the events they are encountering, giving investigators critical information about their decision making. For example, in the January 1982 accident of a Boeing 737 that crashed in Washington, D.C., cockpit voice recorder information showed that neither pilot understood the meaning of engine performance display data (National Transportation Safety Board, 1982).

The flight had been delayed during a snowstorm. To speed their departure from the gate, the captain inappropriately applied reverse thrust, designed to redirect jet engine thrust forward to slow the airplane on landing. On some aircraft, reverse thrust was permitted for exiting the gate area. However, on airplanes with wing-mounted engines, such as the Boeing 737, the engines are close to the ground and the use of reverse thrust in the terminal area could redirect debris into the front of the engines and damage them.

The pilot's use of reverse thrust at the gate caused snow and ice to block critical engine probes in the front of the engines, invalidating the data that several of the five engine displays presented. Four gauges, which displayed data from internal engine functions, presented accurate information. With two engines on the Boeing 737, five engine-related displays were presented in each of two columns, one for each engine, a total of 10 gauges in all. The two accurate displays were located in the topmost of the five rows (Figure 10.2), the ones that measured engine RPM and were not dependent on the blocked engine probes, as were the gauges in the remaining four rows. The analog gauges presented conflicting information that digital displays in modern aircraft would likely display as well (because of regulator requirements on engine data to be displayed), but with associated warnings on other displays indicating the discrepancies between the presentations.

After he applied takeoff thrust, the first officer recognized that the engine instruments were providing unexpected information. Yet, neither pilot could understand the nature of the unfamiliar data, or the significance of the presented information, a diagnosis they attempted to achieve while the airplane was rolling for takeoff and thus, just seconds before a decision needed to be made as to whether to continue the takeoff or stop the airplane on the remaining runway while it was still safe to do so. Neither pilot appeared to have encountered the data previously, either in training or during an actual flight. The first officer asked the captain, "That don't seem right, does it?" Three seconds later he again said, "Ah that's not right." The captain responded, "Yes it is, there's eighty [knots]." Almost immediately, the first officer answered, "Nah, I don't think that's right." Nine seconds later he again expressed uncertainty, "Ah, maybe it is," he said. Four seconds later, after the captain declared that the airplane's speed had reached 120 knots, the first officer said simply, "I don't know." They continued with the takeoff, and the accident occurred 38 seconds later.

The pilots' comments, with other data, showed investigators that

- The pilots were unable to interpret the displayed engine data in the time available to make an informed go/no-go takeoff decision
- The captain misinterpreted the displayed data
- The first officer was uneasy with the captain's interpretation, and
- He nevertheless acceded to it

This information allowed investigators to understand the nature of the crew's decision making and suggest strategies to improve pilot performance in similar situations.

Recorded audio data can also allow investigators to compare changes in operator vocalizations, potentially revealing much about operator performance. For example, investigators of the 1989 grounding of the oil tanker *Exxon Valdez*, in Alaska's Prince William Sound, compared changes in the

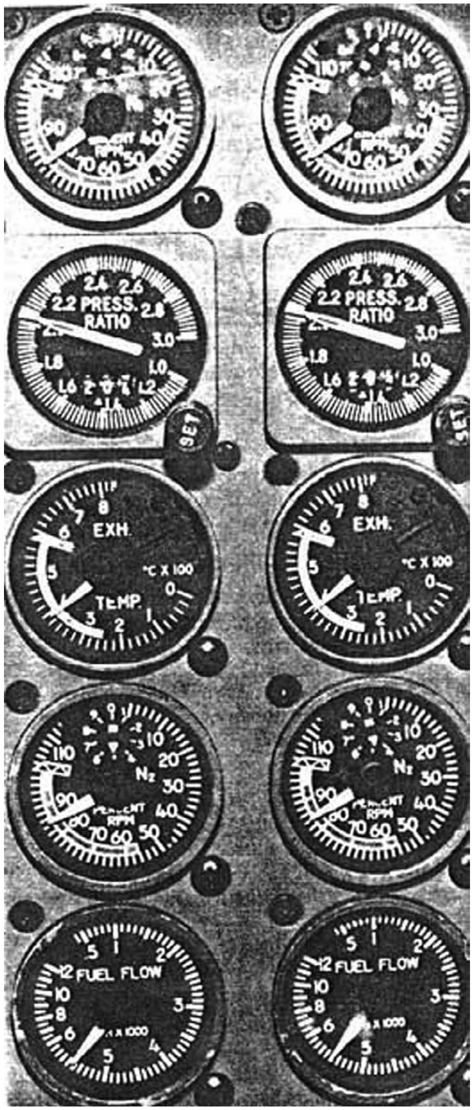

FIGURE 10.2
Engine data for 737-200, resembling displays on accident aircraft. Displays on 2nd row from the top point to the 10:00 position, all others to the 8:00 position. (Courtesy of the National Transportation Safety Board.)

tanker master's voice during communications with the U.S. Coast Guard's Port of Valdez vessel traffic center 33 hours before, 1 hour before, immediately after, 1 hour after, and 9 hours after the grounding (National Transportation Safety Board, 1990). His speech rate significantly slowed, and other vocal characteristics, such as articulation errors, were found that were consistent

with the effects of alcohol consumption. With other evidence, the recorded audio information supported investigators' conclusions that the master was impaired at the time of the grounding, and that his alcohol-related impairment contributed to the accident.

The Equipment

Recorded data can disclose critical features of aurally presented information such as alerts, their sound characteristics, time of onset and of cessation, and operator statements in response to these sounds. Investigators used this information in their investigation of a 1996 Houston, Texas, accident in which the pilots of a DC-9 failed to extend the landing gear before landing, causing substantial damages to the airplane (National Transportation Safety Board, 1997a).

Airplanes are required to have alerts that sound if the pilots do not extend the landing gear before landing. Investigators sought to determine whether the warnings alerted, and if so, the nature of the pilots' response. Cockpit voice recorder data revealed that the pilots had omitted a critical step on the pre-landing checklist, which called for one pilot to engage the hydraulic system, the mechanism that powers the flaps and the landing gear, and the other to verify that the system had been engaged. However, because they had omitted this step and did not engage the hydraulic system, they were unable to extend the flaps and landing gear. Although they knew that they could not lower the flaps, the cockpit voice recorder indicated that they did not realize that they had not extended the landing gear.

Cockpit voice recorder information revealed that an audible alert, indicating a retracted landing gear, sounded before landing. Concurrently another more prominent alert, the ground proximity warning system alert, was also heard. The simultaneous sound of the two alerts (a result of a single phenomenon, the retracted gear), interfered with the pilots' ability to determine the cause of the alerts. Instead, they focused on maintaining a safe landing profile and did not recognize that the gear had not been extended.

Audio recorders may, on occasion, document information that they had not been designed to capture. For example, in the Washington, DC, Boeing 737 accident discussed previously, the cockpit voice recorder recorded changes in the engine pitch, corresponding to increases in engine thrust for the takeoff. Investigators analyzed these sounds to measure the approximate amount of thrust that the engines generated; a parameter that flight data recorders capture today but did not at that time.

The analysis showed that the amount of thrust actually generated was considerably less than the amount the pilots had attempted to establish, and less than what they believed the engines had been generating. As shown in Figure 10.2, the amount actually generated was consistent with data that the top two rows of the 10 engine-related gauges displayed, the gauges on which the captain was primarily focusing, but inconsistent with data that the other gauges displayed. The discrepancy between the amount of engine thrust actually

generated and the amount the pilots expected proved critical to understanding the accident. The thrust actually generated was insufficient to overcome other adverse weather-related characteristics of the flight. However, because the pilots focused primarily on the two gauges that displayed the engine RPMs, believing that it would indirectly show the amount of thrust actually generated, they were unable to understand or resolve the discrepancy.

System-State Recorders

System-state recorders can provide data captured in the period leading up to and through the event that give extraordinary insights into operator actions and system responses. In railroad operations for example, event recorder data describe several aspects of system responses to engineer actions, data that alone would be quite valuable, but when combined with other data, such as obstructions to visibility, track curvature, grade, and bank angle, the information could enable investigators to identify antecedents to operator errors and understand their effects on operator performance.

The value of system-state recorder information was evident in the investigation of the January 1997 crash of an Embraer Brasilia, in Michigan (National Transportation Safety Board, 1998b). The flight data recorder captured 99 parameters of airplane performance, information that, combined with other recorded data from the cockpit voice recorder, air traffic control radar and communications, and meteorological sources, gave investigators a comprehensive understanding of the state of the airplane and of the operator actions up to the accident.

These data showed that the pilots had slowed the airplane to a speed that would ordinarily have been acceptable for safe flight. However, analysis of the airplane's flight path suggested that it had likely passed through an area of icing just before the accident, leading to ice accumulation that investigators determined was likely imperceptible. Its flight characteristics were consistent with those of an aircraft adversely affected by ice accumulation on its wings. Although the airspeed would otherwise have been adequate, the ice accretion caused a control loss at the particular airspeed that the pilots had established in those meteorological conditions because ice contamination on an airplane's airfoil or wing increases the speed at which the airplane will stall. What had been an acceptable speed for safe flight became an insufficient speed because of the ice contamination.

Integrating Information from Multiple Recorders

When combining data recorded in different recorders, applying a common standard or metric to align and match the data helps to clarify the often diverse information. Because many recorders capture elapsed time, the use of a standard time common to the various recorded data allows investigators to compare data from multiple recorders. For example, this process

allows one to compare operator statements obtained from audio recorders to parameters obtained from system recorders, to assess changes in operator statements that may relate to changes in other system features.

Investigators of the May 1996, DC-9 accident in the Florida Everglades, plotted the data from the flight data recorders, cockpit voice recorder, and air traffic control radar on one diagram to create a three-dimensional plot of the airplane's flight path, displayed in Figure 10.3 (National Transportation Safety Board, 1997b). By comparing data from the three sources of recorded information, investigators found that,

> The flight was normal until 1410:03, when an unidentified sound was recorded on the cockpit voice recorder. At 1412:58, after about 30 seconds at 7,400 feet msl altitude with a gradual heading change to 192°, the radar indicates an increasing turn rate from the southerly direction to the east and a large increase in the rate of descent. Flight 592 descended 6,400 feet (from 7,400 feet to 1,000 feet) in 32 seconds. Computations of airspeed, based on radar data, indicate that the airspeed of flight 592 was more than 400 KIAS and increasing at the time of ground impact, which occurred about 1413:40. (pp. 55, 58)

The constructed plot, Figure 10.3, shows the flight path, altitude, and position of the airplane, selected background sounds, and pilot statements to

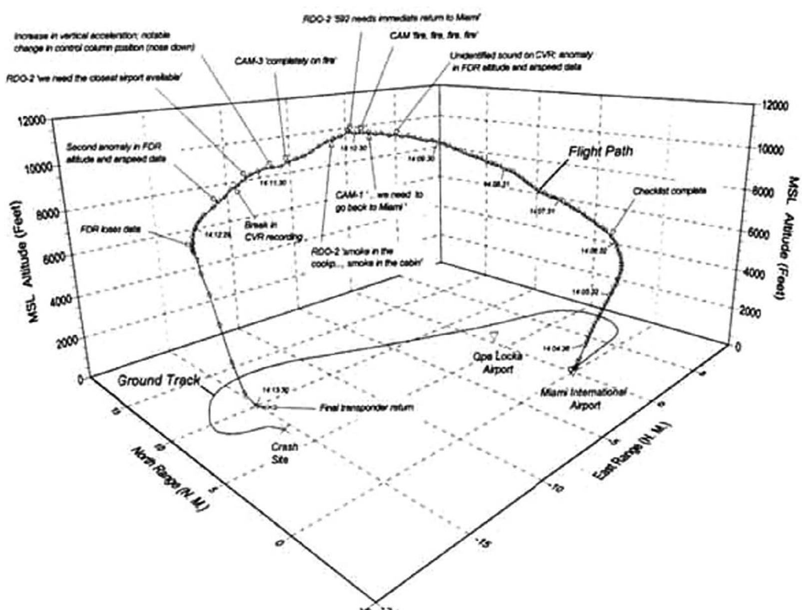

FIGURE 10.3
Ground track of ValuJet flight 591, using information from air traffic control radar, and cockpit voice and flight data recorders. (Courtesy of the National Transportation Safety Board.)

air traffic controllers. The plot presents a readily interpretable picture of the airplane's path, as the pilots gave controllers increasingly urgent accounts of the smoke and fire in the airplane.

Assessing the Value of Recorded Data

Audio Recorder Data

The quality of the recording components and the level of ambient noise affect the quality of audio recorder data. Defects in microphones, recording media, and drive speed, can degrade the recorded sound quality and detract from the ability to identify and interpret the sounds. The distance of the microphone from the operators or system sounds also affects sound quality, unless microphones that are designed to detect sounds at great distances are used. In general, the greater the distance between the microphone and the sounds that are being recorded, the lower the quality of the recorded data.

System-State Recorder Data

The quality of system-state recorders, though relatively immune to many of the features that could degrade audio recorder data, is primarily influenced by two factors, the frequency with which the data are sampled, and the number of system parameters that are recorded. Because at any one point complex systems measure a potentially unlimited number of parameters, the more parameters that are sampled and recorded, the more comprehensive the subsequent portrait of the system. Recorders that capture hundreds of system parameters provide a more comprehensive, and hence more valuable, description of the system and its operating environment than those that record only a few parameters.

Similarly, because of the dynamic nature of many complex systems, the more often system recorders obtain and record the data, the more accurate the view of the system that is obtained. A device that captures data every second gives a more complete, and hence more accurate, account of system operations than one that captures data every third second.

Summary

Many systems are equipped with equipment that records critical information about system equipment, components, operating environments, and

operator actions. Because of technological innovations and other factors, relatively inexpensive video cameras are often found in or near accident sites, thus potentially providing valuable information about a system in the moments before an accident. Images from video recordings can be applied in innovative ways to enhance investigators' understanding of accident causation. Audio recorders chronicle operator comments and other sounds heard in operating stations, and system-state recorders record key system parameters.

INTERPRETING RECORDED DATA

- Match pertinent data against a common metric, such as elapsed time, local time, or Universal Coordinated Time, also referred to as Greenwich Mean Time, when examining data derived from multiple recorders.
- Select the parameters that best reflect the overall system state, the components of greatest benefit to the issues of the investigation, and that offer the most information on operator decisions and actions, if considerable recorded data are available.
- Develop multiple data plots, or use multiple time intervals as the period of interest increases or decreases, when numerous system-state parameters have been recorded.
- Determine an appropriate interval to be used when examining recorded data, taking into account the number of parameters, the proximity to the event, and the number of changes that the system is undergoing at the time.

References

Brown, M. T. 1999. Marine voyage recorders. Proceedings of the International Symposium on Transportation Recorders (pp. 47–60). Washington, DC: National Transportation Safety Board.

Dobranetski, E. and Case, D. 1999. Proactive use of recorded data for accident prevention. Proceedings of the International Symposium on Transportation Recorders (pp. 99–120). Washington, DC: National Transportation Safety Board.

Fenwick, L. 1999. Security of recorded information. Proceedings of the International Symposium on Transportation Recorders (pp. 145–151). Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1982. Aircraft accident report. *Air Florida, Inc., Boeing 737-222, N62AF, Collision with 14th Street Bridge, near Washington National Airport, Washington, DC, January 13, 1982*. Report Number: AAR-82-08. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1988. Aircraft accident report. *Northwest Airlines, Inc., McDonnell Douglas DC-9-82, N312RC, Detroit Metropolitan Wayne County Airport, Romulus, Michigan, August 16, 1987*. Report Number: AAR-88-05. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1990. Marine accident report. *grounding of U.S. rankship Exxon Valdez on Bligh Reef, Prince William Sound, Near Valdez, Alaska, March 24, 1989*. Report Number: MAR-90-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1991. Aircraft accident report. *Grand Canyon Airlines, flight Canyon 5, De Havilland Twin Otter, DHC-6-300, N75GC, Grand Canyon National Park Airport, Tusayan, Arizona, September 27, 1989*. Report Number: AAR-91-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997a. Aircraft accident report, wheels-up Landing. *Continental Airlines flight 1943, Douglas DC-9, N10556, Houston, Texas, February 19, 1996*. Report Number: AAR-97-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997b. Aircraft accident report, in-flight fire and impact with terrain. *ValuJet Airlines, flight 592, DC-9-32, N904VJ, Everglades, Near Miami, Florida, May 11, 1996*. Report Number: AAR-97-06. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1998a. Railroad accident report. *derailment of Amtrak Train 4, Southwest Chief, on the Burlington Northern Santa Fe Railway, near Kingman, Arizona, August 9, 1997*. Report Number: RAR-98-03. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1998b. Aircraft accident report, in-flight icing encounter and uncontrolled collision with terrain. *Comair flight 3272, Embraer EMB-120RT, N265CA, Monroe, Michigan, January 9, 1997*. Report Number: AAR-98-04. Washington, DC.

National Transportation Safety Board. 1999. Aircraft accident report, uncontrolled descent and collision with terrain. *USAir flight 427, Boeing 737-300, N513 AU, Near Aliquippa, Pennsylvania, September 8, 1994*. Report Number: AAR-99-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2000. *Safety Recommendations A-00-30–A-00-31, April 11, 2000*. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2008. Heeling accident on M/V Crown Princess. *Atlantic Ocean off Port Canaveral, Florida, July 18, 2006*. Report Number: MAR-08-01. Washington, DC: Author.

Wald, M. 1999. Secret witness to car crashes in black boxes. *The New York Times*, May 30.

11

Interviews

> Did I see DiMaggio famously kick the dirt as he reached second, a moment replayed on countless television biographies of him because it was the rarest display of public emotion on his part? Again, I think I did. Who knows? Memory is often less about truth than about what we want it to be.
>
> **Halberstam, 2000**
> *New York Times*

Interviews can provide information unobtainable from other sources and give investigators unique insights into critical operator errors. Their value is undeniable and nearly all investigations rely heavily on interviews. Yet many investigators conduct interviews poorly, largely because they do not recognize that interviewing, like other aspects of investigations, calls for unique skills. Experienced interviewers understand that the conduct of an interview can affect its outcome. No information collected in an investigation is as susceptible to variations in investigative technique as are interview data. The interviewees selected, the questions asked, and the interviewing methods used, are just some of the elements that can affect interview quality. This chapter will examine interview quality and discuss methods to enhance the quality and quantity of interview information.

Memory Errors

To understand interviewing skills, it is necessary to first understand how memory functions and what influences memory errors. Research has shown that people do not passively receive and record information as memories, rather they actively reconstruct memories (Buckhout, 1974; Haber and Haber, 2000). As researchers have described it,

> In essence, all memory is false to some degree. Memory is inherently a reconstructive process, whereby we piece together the past to form a coherent narrative that becomes our autobiography. In the process of reconstructing the past, we color and shape our life's experiences based on what we know about the world. Our job as memory researchers and as human beings is to determine the portion of memory that reflects

> reality and the portion that reflects inference and bias. This is no simple feat, but one worthy of our continued investigation. (Bernstein and Loftus, 2009, p. 373)

Memory reconstructions and hence memories are influenced by people's experiences, attitudes, motives, and beliefs. Because of differences among these influences and other differences those experiencing the same event may have different memories of it. This can be especially true for dynamic events, as Buckhout (1974) explains, describing various influences on the accuracy of recollections of dynamic events,

> The length of the period of observation obviously limits the number of features a person can attend to. Yet, fleeting glimpses are common in eyewitness accounts, particularly in fast-moving situations. Less than ideal observation conditions usually apply; crimes [and incidents and accidents] seldom occur in a well-controlled laboratory. Often distance, poor lighting, fast movement or the presence of a crowd interferes with the efficient working of the attention process. (p. 25)

Errors in the recall of dynamic events were evident in the information that over 670 eyewitnesses gave investigators in the investigation of the 1996 in-flight explosion of a Boeing 747 off the coast of Long Island, New York (National Transportation Safety Board, 2000). Over 250 of the eyewitnesses described aspects of the event that were directly contradicted by the physical evidence; they claimed to have seen a streak of light or flame ascend to the airplane. However, the physical evidence was unequivocal; flames fell from the airplane, not the other way around.

Hyman (1999) describes three categories of memory errors that people can make: incorrectly reconstructing event recollections, incorrectly attributing the source of information, and falsely believing that events that were not experienced had been experienced. To Hyman, memory errors occur because people "view the event as plausible, they construct a memory that is partially based on true experience and that is often very vivid, and they erroneously claim the false memory as a personal recollection" (p. 247). In other words, people may reconstruct memories by applying information from their previous experiences to fill in gaps, or to help explain phenomena they observed that were difficult to explain.

Interviewers can also influence interviewee recollection and response. Loftus (1997) showed that interviewers can subtly insinuate false information into their questions, which interviewees may then believe as facts witnessed or experienced. Wells, Malpass, Lindsay, Fisher, Turtle, and Fulero (2000), summarizing the literature on eyewitness recollection errors, conclude that,

> The scientific proof is compelling that eyewitnesses will make systematic errors in their reports as a function of misleading questions. From a system-variable perspective, it matters little whether this effect is a result

> of introducing new memories or altering old memories or whether this is a compliance phenomenon. The important point is that witnesses will extract and incorporate new information after they witnessed an event and then testify about that information as though they had actually witnessed it. (p. 582)

Nevertheless, despite the potential for memory errors, witnesses can provide valuable information. Knowing the influences on memory, it is incumbent on interviewers to recognize the substantial influence they can exert on the quality of the interview itself and take steps to enhance interviewee recall and reduce opportunities for memory errors. Interviewers should begin to do this even before they begin the interview.

Interviewees and Their Concerns

Some interviewees have much at stake in the findings of an investigation while others have little or nothing at stake. Differences in background, experience, and education can also affect people's ability to understand and respond to questions, and their willingness to assist an investigation.

Interviewees in accident and incident investigations generally fall into one of three groups, according to their relationship with the operator or their role in the event. These include those who have observed the event, operators whose actions are the primary focus of the investigation, and those who are familiar with critical system elements but may not have been directly involved in operating the system at the time of the accident. Each may have important information to contribute, according to his or her knowledge and insights.

Eyewitnesses

Eyewitnesses to an event may have observed features that system recorders did not capture, heard noises beyond the microphone range, smelled odors associated with certain phenomena, or felt movement that no device recorded. Their observations and experiences may enhance or confirm existing information and add to information unavailable from other sources.

Eyewitness willingness to cooperate with investigators will likely be influenced by their confidence in the value of the information they can provide the investigation, and possible concern with the interviewer's approval of their responses. They will likely offer information more readily if they believe both that it will help the investigation and that interviewers will appreciate their cooperation. Thus, it is incumbent on those interviewing eyewitnesses to unambiguously describe the potential contribution of the eyewitness to the investigation, and convey the investigators' appreciation to them for their cooperation.

System Operators

Operators may be able to describe their actions and decisions during the event and provide helpful background information about the system. However, if the event that occurred was dynamic, they may be unable to recall details, and if they feel responsible for the event, they may have difficulty responding. Nonetheless, at a minimum, they should be able and willing to describe their experiences in system operations and thus offer insights regarding system design and company policies and practices. Investigators should recognize that operators may be concerned about the effects of the event on their careers. The accident being investigated may be the most challenging and difficult event they have encountered in their professional experience. If operators' feelings of personal responsibility or career concerns adversely affect their ability to recall events, interviewers can do little other than delay the interview until the operators are sufficiently composed and distant from the event to effectively answer questions.

Those Familiar with Operators and Critical System Elements

Those at the system's "blunt end" in Reason's terms are familiar with critical elements of the system. They serve as the equipment designers, training managers, procedures specialists, financial managers, or direct supervisors. Their decisions and actions may have set in motion the circumstances that led to the errors of the operators at the "sharp end."

Those close to the operators, such as family and coworkers, may share many of their concerns. Depending on the information and the availability of the operators, investigators should obtain from them details about recent operator experiences such as sleep and work habits, and recently encountered stressful events. This information may give investigators better insight into the event than they might otherwise obtain.

Operators or those familiar with them may also feel responsible for the cause of the event. For example, a maintenance supervisor may believe that he or she was responsible for the errors of the technicians whom he supervised, or for the quality of the procedures that he followed. Unfortunately, little can be said to address these concerns. These interviewees could describe their decisions and the actions they took that may have influenced the nature of the event.

Information Sought

The information sought in an investigation varies according to the role of the interviewee in the event being investigated, whether eyewitness, operator, or someone familiar with critical system elements.

Eyewitnesses

Eyewitnesses should be asked to describe

- What they saw, heard, felt, and smelled
- Details of the event that first caught their attention
- Time of day they witnessed the event
- Their own location and activities during the event
- Operator actions
- The names and locations of other eyewitnesses if known
- Additional information they believe relevant

Operators

Operators should be asked to provide information about the event, and additional personal and company-related information, including,

Event-related actions and decisions

- Decisions they made before the event
- Approximate time when they made those decisions
- Actions they took before the event
- Approximate time when they took those actions
- Outcome and consequences of each

Job/task information

- Their job/task duties and responsibilities in general
- Knowledge requirements of the job/task
- System operating phases and their approximate time intervals
- Their responsibilities, activities, and workload during each operating phase
- Abnormal situations and the frequency with which they have been encountered
- Their responses to abnormal situations

Company practices and procedures

- General system operating practices and procedures
- Task specific practices and procedures
- Differences between company intent and actual practice in system procedures

Personal information

- Overall health and recent illnesses, physician visits, and hospitalizations
- Major changes in family and/or job status
- Medications taken within previous 30 days, including prescribed and over the counter medications, and herbal supplements
- Sleep schedule previous 72 hours (longer if they can recall)
- Activities previous 72 hours (longer if they recall)

Those Familiar with Critical System Elements

Those who are acquainted with the system operators on duty at the time of the accident should be asked for information that is unavailable from other sources, or that adds to existing information about the event. In general, the operator's close relatives or colleagues should be asked about the operator's

- Sleep and rest schedule previous 72 hours
- Activities previous 72 hours
- Opinions expressed toward the job, coworkers, and the company

Those who are familiar with the system should be asked about the following, according to their expertise and role in system operation

- Operator training and work history
- Training program history and description
- Operating policies and practices
- General company policies and practices

The Cognitive Interview

Regardless of the interviewee, interviewers should always ask questions in a way that enhances interviewees' ability to provide the maximum information possible. In the mid-1990s, after a number of people convicted of primarily sexual assault crimes, largely on the basis of eyewitness evidence, were found to have been wrongly convicted after DNA evidence later confirmed their innocence (Loftus, 2013), research into how eyewitnesses misidentified suspects was initiated. The studies showed that in most cases the witnesses fully believed that the individuals whom they had identified were the ones who committed the crimes of which they

were accused, but largely as a result of the manner in which law enforcement officials had interviewed them they had come to identify the wrong individuals.

Around the same time adult women claimed that close relatives had sexually abused them when they were children, but, because of the psychological trauma associated with the assaults, their memories of those assaults were repressed until adulthood. However, as Bernstein and Loftus (2009, p. 372) observed, "many cases of allegedly recovered memories have turned out to be false memories implanted by well-meaning therapists who use suggestion and imagination to guide the search for memories." These often high-profile instances led to research that showed that events that had never occurred could be "planted" into peoples' memories, so that the people firmly believed that the events that they described had in fact occurred. The research also illustrated how memories of events are reconstructed, and that people may, without recognizing it, fill in "gaps" in their observations of events to make "complete" memories. Similar research into interviewing showed that interviewer suggestibility and manner of asking questions affect the responses that interviewees provide. Today, as a result of research into both memory development and interviewing, a number of interviewing techniques have been developed to enhance interviewee recollection. Foremost among them is the cognitive interview, which as researchers describe,

> …represents the alliance of two fields of study: communication and cognition. The social-psychological concerns of managing a face-to-face interaction and communicating effectively with a witness were integrated with what psychologists knew about the way people remember things. (Wells, Memon, and Penrod, 2006, p. 55)

Cognitive interviewing assumes that interviewees want to provide maximum information to interviewers, and by conducting interviews in the appropriate environment with effective techniques, interviewers can maximize the information they obtain in interviews.

Rapport

A critical element of cognitive interviewing calls on the interviewer to establish and maintain rapport with the interviewee. Research has demonstrated that when interviewers establish rapport with interviewees the quality and quantity of information the interviewees provide increases (Collins, Lincoln, and Frank, 2002; Kieckhaefer, Vallano, and Compo, 2014). Interviewer–interviewee rapport can lessen interviewee anxiety and provide a personal connection between the two so that the interviewee will want to assist the interviewer. Interviewers need to establish and maintain rapport with all interviewees, even operators suspected of causing major accidents.

A disapproving tone, lack of concern, and subtle expressions of disapproval can quickly make the interviewee reluctant to provide additional information to the interviewer. By contrast, concern for the interviewee's well-being, a neutral tone, close attention to the interviewee can enhance rapport and hence, the amount of information provided.

Geiselman and Fisher (2014) recommend that before beginning interviews, interviewers exchange pleasantries with interviewees by asking them what they do on a typical day, describe family activities, and so on. Additional techniques include explaining to the interviewee the role of interviewee information in the investigation, how the information will assist investigators, and attending to interviewee needs and concerns throughout the interview.

Because of the importance of personal contact in establishing rapport, particularly when interviewing operators and others knowledgeable about the system, interviewers should conduct face-to-face interviews when possible rather than by electronic means such as video and/or audio interactions, available through various telephone, software, and smart phone apps. However, practicality of investigation is also important and thus if interviewers need to question numerous eyewitnesses and sufficient interviewers are not available, face-to-face interviews with the eyewitnesses may not be practical. In that case, conduct interviews by other electronic means such as through computer-based video or audio.

Asking Questions

The cognitive interview assumes that interviewees maintain memories of the events they are asked to describe, and that the best way interviewees can access those memories is to allow them to follow their own memories rather than the interviewer attempting to direct the interviewee to do so. That can be done most readily by asking the interviewee open-ended questions, and then, based on the responses, following up with more specific ones. For example, good opening questions include, "tell me what happened when you first realized that something was wrong," "what did you see when the train approached the curve," and "what happened as you began to slow down." Follow up questions to these open-ended ones can be of the type, "what did you do next," "what happened after that," and "what was your colleague doing at this time."

A technique that many interviewers use, which forces them to listen to interview responses, is to avoid writing questions in advance, but instead writing topics that need to be addressed beforehand. As each topic is covered they cross off that item and proceed to the next one. By focusing on the interviewee responses, interviewers can follow up with questions that correspond to the train of thought of the interviewee, rather than disrupting that and thereby interfering with his or her ability to access memory of the

event. Also, by adhering to topic rather than question, interviewers allow interviewees to focus on single topics at a time, thus minimizing disruption to their memories. Exceptions to adhering to topics should only be made if the interviewee response calls for it. That is, if the interviewee himself or herself, in the response, jumps to another topic, it would be appropriate to follow up with a question related to that topic, if asking the interviewee to elaborate or provide more detail to the answer just given.

Interviewers should strive to keep their questions as brief as possible. The less the interviewer talks, the more that the interviewee will be encouraged to do so. In this manner, if interviewees pause during a response, interviewers should wait as long as appropriate to allow the interviewees to fully recollect their thoughts and complete their responses. Even if the pauses are longer than would typically occur in a conversation, interviewers should avoid intruding on interviewee thoughts until they are certain that the interviewee has completed a response.

By the same token, questions that ask for yes or no responses should be avoided as they limit the potential information interviewees are asked to provide. Interviewers should also avoid asking leading questions, for example, did you see the explosion that occurred, and instead ask an open-ended question in its place, for example, what did you see, also in an effort to encourage the interviewee to provide as many details as he or she can recall.

False Responses

Accident investigations, unlike forensic or criminal investigations, do not aim to identify a perpetrator of a crime but to understand the cause of an accident. Although in some jurisdictions operators whose errors have led to accidents may be prosecuted for their role in the accidents, to the accident investigator the more cooperative the interviewer can be with the interviewee the more information the interviewee can be reasonably expected to provide, independent of prosecutor actions. Thus, it behooves interviewers to avoid approaching the interviewee as someone who has potentially caused an accident but rather, as someone whose information can assist to prevent future accidents. Nonetheless, interviewers may encounter interviewees who believe that they have something to hide, even when they face no criminal or civil action as a result of the accident.

When encountering an interviewee who is believed to be answering questions falsely, accusing the interviewee of such will do little to enhance cooperation. After all, the interviewee may be telling the truth. Rather, the best approach is to rephrase the question, perhaps repeat the question, and then move on to a different topic. The fact is that interviewers have little ability to get interviewees to change their responses when answers are believed to be false.

Finding, Scheduling, and Selecting a Location for the Interviews

Eyewitnesses

Local media, law enforcement and rescue personnel, as well as those working near the event, often establish contact with eyewitnesses. Law enforcement and rescue officials are usually the first to arrive at the scene, are experienced in locating witnesses, and can encourage them to cooperate with investigators. As such they may be able to assist investigators in identifying and locating eyewitnesses. In addition, media representatives, who generally arrive on scene quickly and are usually adept at locating and interviewing eyewitnesses, may also be able to help locate eyewitnesses. Media representatives can also be asked to inform the public of a need for eyewitnesses and thus, help disseminate to eyewitnesses the investigators' need for their assistance.

Scheduling the Interview. There is usually extensive media attention and general discussion after a major accident, and eyewitnesses have difficulty avoiding exposure to accounts of the event. Therefore, eyewitnesses should be interviewed as soon after the event as possible to reduce their exposure to potentially contaminating information and other adverse influences on their recall.

Selecting a Location for the Interview. Eyewitnesses may recall more of an event at the locations at which they witnessed it. Reencountering the cues associated with the event, such as buildings, objects, hills, or trees may help them remember additional information (Fisher and Geiselman, 1992). However, if doing so will delay interviewing others, the delay could outweigh the advantages of site-related memory enhancements. Consequently, if eyewitnesses can be interviewed quickly at the locations at which they observed the event one should do so, but otherwise the interview should not be delayed.

Operators

The company managing the system should be able to coordinate interviews with operators who were on duty during the event.

Scheduling the Interview. Operators, as other interviewees, are subject to memory contamination and this would ordinarily call for interviewing them quickly after an event. However, two factors argue for delaying their interviews for 24- to 48-hours after the event. First, it often takes several days to obtain even routine system-related information after an event. Delaying operator interviews allows investigators to examine records, talk to eyewitnesses, and learn about the event, enabling them to ask more sophisticated questions about the event, and increasing the value of information they would likely obtain immediately after an event. Second, operators involved

in a major event are often distraught and may have difficulty concentrating. Delaying the interview allows them to compose themselves. A 1- to 2-day delay after the event is usually sufficient to serve both operator and interviewer needs.

If the operator was injured in the event, it is important to obtain the attending physician's approval before the interview. The physician should be able to assure you that the operator would not be harmed by the interview, is capable of comprehending and responding to questions, will not have answers affected by the medications prescribed, and will have full awareness of the interview. If the physician cannot so assure you, wait until after the operator has ceased to use the medications, when they are no longer in his or her system, and he or she is otherwise able to fully comprehend and respond accurately to questions before initiating the interview.

Selecting a Location for the Interview. The location of an operator interview is critical. The wrong setting could increase the operator's anxiety and discomfort, and thus hamper his or her recall. Ideally, operators should be interviewed in a professional setting, free of distractions such as busy hallways, elevators, and noisy streets, and equipped with comfortable chairs and a table or desk. A hotel conference or meeting room is often a good choice. Telephones, pagers, cell phones, and other potential distractions should be disengaged or turned off, window shades or curtains drawn to minimize outside distractions, and thermostats set to a comfortable temperature. Operating and training manuals and other pertinent material should be accessible. Finally, water or other refreshments for the operator should be available throughout the interview.

When an operator is having difficulty recalling events, conducting the interview in a system mock up or simulator may enhance recall. If this is not possible, diagrams or photographs of system components, and equipment used at the time of the event, should be provided for reference.

Those Familiar with Critical System Elements

Company management should assist in finding and scheduling interviews with company personnel. They can also usually help to find friends and close family members of the operators if needed.

Scheduling the Interview. It is not critical to minimize the exposure to memory contaminants of those who are familiar with critical system elements, and these interviews can safely be delayed for several weeks after the event to allow investigators to complete interviews with those whose recall is more sensitive to the effects of time delays. Nevertheless, family and acquaintances of the operators should be interviewed quickly because their memories of the operator's activities could be contaminated by exposure to subsequent accounts.

Location of the Interview. Whether the interviewee is a family member or a company supervisor, the interview location should be professional and

business-like, free of distractions, and large enough to comfortably accommodate those participating in the interview. Interviewees should have access to reference material, and other helpful items as needed.

Administrative Concerns

Interviewers must attend to numerous logistical and administrative details to ensure a successful interview. These details, which are critical to ensure that interviews result the maximum possible information include

- The interview record
- Operator team members
- Multiple interviewers
- Information to provide interviewees

The Interview Record

The interview's written record is the medium through which interview data are conveyed to others. Deficiencies in the record lessen its value, regardless of the overall interview quality. Several interview documentation methods are available, each with particular advantages and disadvantages.

Video or audio recordings provide the most accurate interview record and usually require the least interviewer effort during the interview. Therefore, if possible, investigators should strive to record the interview. Interviewees generally adapt quickly to the presence of recording equipment. Interviewers must also follow appropriate rules governing interview recordings because some jurisdictions prohibit recording interviews without interviewee approval and interviewees may be unwilling to permit recording their interviews.

Professional transcribers or court reporters can generate interview transcripts, however the cost may be substantial and transcribers are often unfamiliar with technical terms that may arise. In addition, they are more obtrusive than recording devices, although interviewees in time usually adapt to their presence as well.

Interviewers who are adept keyboarders can also enter interviewee responses directly into a laptop or tablet during an interview, an inexpensive alternative to transcribing the interview. Spell-checkers facilitate this method by allowing keyboarders to input the data quickly without the need for much accuracy. However, interviewers may find it difficult to ask questions, follow the responses, and keyboard the responses simultaneously. Many laptops and tablets also allow an audio interview record to be entered

directly onto audio files, thus providing an audio interview record to support transcribed notes.

The common method of preparing a written record calls for interviewers to write their own notes taken during the interview and add more details from memory afterward. This method is inexpensive and requires little writing skill, but it is the least accurate of the interview documentation techniques. If multiple interviewers participate in the interviews, they should combine their notes after completing the interview, to provide a single complete set of interview notes.

Operator Team Members

Operator team members should be interviewed individually, and not in the presence of other team members, to reduce the likelihood that one would influence another's responses. Operators should also be asked not to discuss the interviews with their colleagues, although enforcing this prohibition may be difficult.

Multiple Interviewers

The number of interviewers should be kept to the minimum possible to maximize interviewer–interviewee rapport. The lower the number of interviewers who are present, the less intimidating the process will be to the interviewee and the more readily interviewer and interviewee can establish rapport. However, multiple interviewers can also enhance the interview by interviewing numerous eyewitnesses simultaneously, increasing the efficiency of the interview, and in the case of operators or those familiar with system elements, by bringing additional perspectives to the interview, thus increasing the interview scope and depth.

To avoid potential administrative difficulties among multiple interviewers, it is important to establish and maintain guidelines governing the conduct of the interviews to enhance the likelihood that the interviews go smoothly. These guidelines should be articulated, understood, and agreed upon before the interviews begin. These should include identifying the lead questioner, establishing the order in which interviewers question the interviewee, and determining how to deal with interruptions.

Order of Interviewers. The lead interviewer is generally the group's leader and therefore, the person who generally questions the interviewee first and sets the tone of the interview. Thereafter, each interviewer should be given the opportunity to ask an initial set of questions and at least one set of follow up questions, in the order appropriate to the group.

Interruptions. Interruptions to either interviewees or interviewers should be avoided, except when an interviewee does not understand the question or his or her response has deviated from the thrust of the question. In that event, only the lead interviewer should be permitted to bring the discussion

back on track. Otherwise, interviewers should note additional questions they may have, and then ask those questions during follow up questioning.

Information to Provide Interviewees

Before the interview, interviewers should identify the information that they will be willing to provide interviewees. In general, information that cannot be shared with those outside the investigation, is speculative or analytical, or can influence the recollections of subsequent interviewees, should not be discussed.

Concluding the Interview

Conclude the interview when all pertinent information sought from the interviewee has been obtained, and when it is clear that the interviewee has no additional information to offer. Interviewers should not have difficulty determining when they have reached this point. Interviews should not be concluded for other reasons, such as the need to attend to other investigative activities. If a potential conflict can interfere with an interview the interview should be rescheduled at a time when it can be conducted without disruption.

After responding to all questions, interviewees should be asked whether they have additional information to offer, and if there are important questions about the event that they had not been asked. Interviewers should then ask the interviewees whether they have questions, and give them previously agreed upon information, as needed. The lead interviewer should then give the interviewees his or her business card or contact information. Finally, interviewers should thank the interviewees for their cooperation and assistance to the investigation.

Interpreting Interview Data

Because of the many factors that could influence interviewee responses, interview data should not be considered in isolation, but only in conjunction with other investigative data.

Eyewitnesses

Information from eyewitnesses should be used to supplement, but not supplant, other data because of the potential contamination of their recollections. Nonetheless, eyewitnesses can add details that may not be available from other sources. However, if data from more accurate and reliable sources contradict eyewitness data, credence should be given to the more reliable data.

Operators

Operators' first-hand experiences in the complex system in which the event occurred can considerably enhance ones's understanding of the nature of critical errors. Operators with good recall of the event, who sincerely wish to help the investigation, can provide data that simply cannot be obtained elsewhere. Nevertheless, do not be surprised if operators have difficulty recalling specific details in the very dynamic or stressful environment in which events in complex systems often unfold. They are often so engrossed in responding to the event and preventing an accident that they may have difficulty afterward recalling details about that event.

Those Familiar with Critical System Elements

System managers, designers, and others who are knowledgeable about a system can provide information that complements information from other sources. For example, instructors can describe the meaning of comments found in training records, managers can explain the intent that lay behind statements they wrote in performance appraisals, and equipment designers can describe their design philosophy and its manifestation in the operating system. Those operating in the system's blunt end can help explain the development of operating procedures, training programs, and other potentially critical investigative issues.

The value of the information that family and acquaintances of the operators provide depends on the availability of other supporting information, as well as on the relevance of the data to the event. Family and acquaintances of the operators can provide especially valuable information when there is little information available from other sources. Family members or friends of operators injured or otherwise unavailable may be able to give investigators accounts of the operators' activities in the 72 hours before the accident, while their colleagues can describe their work habits and attitudes to investigators.

Summary

People are subject to memory errors, but interviewers can exercise some control over potential influences on these errors and increase the amount and value of the information interviewees provide. Error investigators generally question three types of interviewees, eyewitnesses, operators, and those familiar with critical system elements. Each interviewee has specific concerns and information to provide. Interviewers seek different information from each interviewee, and should recognize their different needs when eliciting the information.

Interviewers should identify the type of information that the interviewees can provide, and identify the issues to elicit the desired information before the interview. Interviewers should ask questions that correspond to the sequence of issues, by beginning with open-ended questions and following up with more specific questions that address points that the interviewee has made. Suggestions are provided for asking questions and chronicling the information from interviewees, with illustrations of effective and ineffective interviewing techniques.

CONDUCTING INTERVIEWS: THE INTERVIEW PROCESS

- Identify the information sought, then identify and locate interviewees that can provide that information.

STRUCTURING THE INTERVIEW: BEGINNING

- Thank the interviewees for their cooperation.
- Introduce each interviewer to the interviewees, giving titles and affiliations, if multiple interviewers are participating.
- Describe the purpose of the interview and mention the value of the information sought.
- Review the interview guidelines with interviewees and ask them if they have questions before beginning.

THE QUESTION SEQUENCE

- Determine beforehand the order of issues to be addressed in questioning each interviewee.
- Introduce new issues after each issue has been addressed in turn.
- Use one of two types of sequences of issues with interviewees, chronological order or order of importance.
- If important, address issues that the interviewee raised while discussing another issue, even if it means going out of sequence.

FOLLOW-UP QUESTIONS

- Use follow up questions when an interviewer has not pursued an issue that an interviewee has raised, or when an interviewee has raised multiple issues in a response to one question.
- Ensure that other interviewers wait until their turns to follow up on an issue rather than disrupt other interviewers.

- Allow each interviewer at least two opportunities to ask questions, one to ask the initial questions and a second to ask follow up questions.

ATTENDING TO THE INTERVIEWEE

- Show attention to the interviewee at all times.
- Be aware of and avoid nonverbal cues that may unwittingly be sent to the interviewee.
- Ensure that the interviewee is comfortable and that the interview location is free of distractions.
- Stop the interview if interviewees appear uncomfortable or begin to lose their composure.
- Do not offer the interviewee career or personal assistance, but demonstrate concern for the interviewee.

FALSE RESPONSES

- Rephrase or refocus the questions if there is reason to believe that an interviewee has answered questions falsely.
- Do not express disapproval or attempt to coerce a truthful response from the interviewee.
- Do not use a prosecutorial tone in asking questions.

ASKING QUESTIONS

- Begin questions with verbs.
- Keep questions as brief as possible.
- Phrase questions to encourage interviewees to be as expansive as possible.
- Progress to more focused questions that follow up on the points interviewees make in response to initial questions.
- Attend to the interviewee answers and, to the extent possible, base questions on those answers.
- Avoid questions that permit one or two word answers, for example, yes or no, unless following up on a response to a particular interviewee answer.
- Avoid asking questions from a predetermined list, in the predetermined order.
- Identify issues to be addressed and ask questions that relate to those issues.

References

Bernstein, D. M. and Loftus, E. F. 2009. How to tell if a particular memory is true or false. *Perspectives on Psychological Science*, 4, 370–374.

Buckhout, R. 1974. Eyewitness testimony. *Scientific American*, 231, 23–31.

Collins, R., Lincoln, R., and Frank, M. G. 2002. The effect of rapport in forensic interviewing. *Psychiatry, Psychology and Law*, 9, 69–78.

Fisher, R. P. and Geiselman, R. E. 1992. *Memory-enhancing techniques for investigative interviewing: The cognitive interview*. Springfield, IL: Charles C. Thomas.

Geiselman, R. E. and Fisher, R. P. 2014. Interviewing witnesses and victims. In M. St. Yves (Ed.), *Investigative interviewing: Handbook of best practices* (pp. 29–40). Toronto: Thomson Reuters Publishers.

Haber, R. N. and Haber, L. 2000. Experiencing, remembering and reporting events. *Psychology, Public Policy, and Law*, 6, 1057–1097.

Halberstam, D. 2000. Maybe I remember DiMaggio's kick. *New York Times*, October 21, 2000.

Hyman, I. E. 1999. Creating false autobiographical memories: Why people believe their memory errors. In E. Winograd, R. Fivush, and W. Hirst (Eds.), *Ecological approaches to cognition: Essays in honor of Ulric Neisser* (pp. 229–252). Mahwah, NJ: Erlbaum.

Kieckhaefer, J. M., Vallano, J. P., and Compo, N. S. 2014. Examining the positive effects of rapport building: When and why does rapport building benefit adult eyewitness memory? *Memory*, 22, 1010–1023.

Loftus, E. F. 1997. Creating false memories. *Scientific American*, September, 70–75.

Loftus, E. F. 2013. 25 years of eyewitness science……finally pays off. *Perspectives on Psychological Science*, 8, 556–557.

National Transportation Safety Board. 2000. *In-flight Breakup over the Atlantic Ocean, Trans World Airlines flight 800, Boeing 747-131, N93119, near East Moriches, New York, July 17, 1996*. (Report Number AAR-00-03. Washington, DC.

Wells, G. L., Malpass, R. S., Lindsay, R. C. L., Fisher, R. P., Turtle, J. W., and Fulero, S. M. 2000. From the lab to the police station: A successful application of eyewitness research. *American Psychologist*, 55, 581–598.

Wells, G. L. Memon, A., and Penrod, S. D. 2006. Eyewitness evidence: Improving its probative value. *Psychological Science in the Public Interest*, 7, 45–75.

12

Written Documentation

> (a) Each certificate holder shall-
> (1) Maintain current records of each crewmember…that show whether the crewmember…complies with…proficiency and route checks, airplane and route qualifications, training, any required physical examinations, flight, duty, and rest time records.
> (2) Record each action taken concerning the release from employment or physical or professional disqualification of any flight crewmember…and keep the record for at least six months thereafter.
>
> *14 Code of [United States] Federal Regulations, Part 121.683*

Introduction

Investigators routinely obtain and examine information maintained in various types of records during investigations, records that contain information describing characteristics of the systems, operators, and the companies that operate them. Recognizing the value of written documentation and knowing when and how to apply the information they contain to an error investigation are critical investigative skills. In this chapter the types of documentation available to investigators will be reviewed, preparation for examining written documentation discussed, qualitative aspects of the data considered, and the application of the data to various situations examined. The documentation is referred to as "written" although most such records, whether maintained by company, regulator, or small business, are largely electronically stored today.

Documentation

In some industries regulators mandate the data companies are to collect, the frequency and regularity of data collection, and the format of the data maintained. For example, the Federal Aviation Administration requires airlines

to retain substantial information on pilots, airplanes, simulators, training programs, maintenance activities, and dispatch releases. Whether required or not, most companies maintain documentation on employees, procedures, training programs, and the like, information that investigators will want to examine because of their potential relevance to error antecedence. This information can take several forms.

Company-Maintained Documentation

Personnel Records

These contain information pertaining to operators' educational and employment histories, and their current jobs, such as supervisor appraisals, letters of commendation or reprimand, and other relevant material.

Investigators of the grounding of the tanker *Exxon Valdez*, in Alaska's Prince William Sound (National Transportation Safety Board, 1990), used this information to help identify some of the antecedents that led to the grounding. Performance appraisals of the third mate completed 3 years before the accident, the third mate who was the senior officer on the bridge and overseeing the tanker's path at the time of the grounding, had been rated low on several critical performance elements. As investigators report (National Transportation Safety Board, 1990),

> In one performance appraisal as a third mate his "overall effectiveness" had been evaluated as "high," one rating below "outstanding." The two lowest ratings he received as a third mate were given to him while he was on the Exxon Jamestown in 1987 and contained the following comments: "performs adequately" in the rating categories of "seeks advice or guidance at the appropriate time and informs supervisor when appropriate" and "demonstrates thorough knowledge of ship and its handling characteristics." In a summary of employee weaknesses, the evaluator wrote, "He [third mate] seems reluctant or uncomfortable in keeping his superior posted on his progress and/or problems in assigned tasks." (p. 33)

The supervisor's comments gave investigators background information to help understand and explain the errors the third mate committed during the accident, where he failed to inform his superiors of his difficulties attempting to steer the vessel in the confined waters of Prince William Sound. Unfortunately, since then companies have tended to decrease the amount of these types of comments in written documentation, to the detriment of error investigations.

Training Records

Training records contain information on operator training that the company and others have conducted, and may include test scores and other

performance measures. Instructor comments and other information, which go beyond test scores, may also be included.

Medical Records

Company-maintained medical records contain data associated with regulator- or company-mandated medical requirements, such as physical examinations, vision, and hearing evaluations. The records may also include medical information outside of direct company control, such as descriptions of operators' medical evaluations, treatment, and prescriptions that were paid for by company-sponsored medical insurers.

As described in Chapter 10, investigators concluded that the master of the *Exxon Valdez* had been impaired by alcohol at the time of the event. Information in the company's medical records of the master indicated that he had been treated for alcohol abuse about 4 years before the accident. As investigators write,

> An Exxon Individual Disability Report, signed by the attending physician and dated April 16, 1985, showed that the master was admitted to a hospital on April 2, 1985, and "remains in residence at the present time." The report stated: "He is a 38 yo W/M [year old white male] who has been depressed and demoralized; he's been drinking excessively, episodically, which resulted in familiar and vocational dysfunction." A treatment program was suggested that included a recommendation that he be given a leave of absence to get involved in Alcoholics Anonymous, psychotherapy, and aftercare. (National Transportation Safety Board, 1990, p. 32)

Because of the information about the captain that the company maintained in its records, investigators believed that, having this information, the company should have monitored his alcohol use closely. That it was believed that he had consumed alcohol while on duty on the vessel before the accident suggested that its oversight was deficient, and that the rehabilitation program that he had entered was flawed, or his commitment to rehabilitation was poor.

Some operators may attempt to conceal information from their employer about potentially adverse medical conditions, and one should not assume that a company's medical records contain all relevant medical information about an operator. The discussion in Chapter 5 of the 1996 New Jersey rail accident (National Transportation Safety Board, 1997), in which the train operator was unable to recognize the stop signal because of his visual impairment, demonstrates that company-retained medical records may be incomplete. The train operator had successfully hidden his diabetes and the diabetes-related visual impairment from his employer, and the company's evaluation of the operator's vision failed to detect his impairment. Investigators

obtained the information they needed to determine his medical condition from the records of his personal physician.

Documentation Not Maintained by the Company

Sources unrelated to the operator's employer might also retain operator-related information. For example, financial, legal, and family records, as well as records of driving history, may reveal aspects of an operator's behavior that, although not necessarily job-related, may nevertheless affect performance.

The information may reveal the presence of stressors that could degrade operator performance. The value of the information depends on the relationship of this information to antecedents to these errors. However, unlike company-maintained documentation, access to such information may be restricted by regulation to law enforcement personnel, and error investigators may need their assistance to examine it.

Information from Legal Proceedings

Pending civil actions or criminal charges are stressors and may adversely affect operator performance. To take an extreme example, nearly all would consider criminal charges and a possible prison sentence to be stressful. By contrast, pending civil action may not necessarily be stressful. Although many find civil action stressful, others do not, particularly if they are not liable for financial penalties or legal expenses. For example, in the United States drivers involved in automobile accidents could be sued for damages that considerably exceed the direct costs of the accident itself. However, because most jurisdictions require drivers to be insured for protection against such losses, the accident-related expenses may be negligible and therefore, the experience may not necessarily be stressful because the drivers may not incur financial costs as a result of the experience.

Family-Related Information

Family-related information may reveal likely stressors such as divorce, child custody disputes, or similar experiences.

Driving History

A record of an operator's driving transgressions may suggest a pattern of behaviors, attitudes, and substance dependencies that are pertinent to an error investigation. Because many operators are exposed to law enforcement authorities when driving, those with records of infractions for driving while intoxicated may also manifest an alcohol or drug dependency because the infractions suggest an inability to avoid alcohol use outside of the work setting (McFadden, 1997).

Nevertheless, it must be noted that while information contained in driving history and similar written documentation may relate to operator antecedents that information pertains to events occurring outside of the system. Therefore, the information should not be applied directly to the examination of the errors, but should instead complement other data about the operator. The data can also suggest avenues of inquiry that investigators may wish to pursue regarding an operator's error, such as possible chemical dependency or financial reverses.

Information Value

As with other accident investigation data, whether from written documentation, recorded media, or interviews, investigators should evaluate written documentation data to assess their value. Quality may vary among and even within a single source such as company records. Poor-quality information contributes little to an investigation, regardless of its relevance to the event.

In general, the factors that can affect the value of written documentation data are

- Quantity
- Collection frequency and regularity
- Length of time since collected
- Reliability
- Validity

Quantity

All things being equal, the more data collected about a parameter the more that is learned about it and the greater the value of the data to the investigation. Similarly, the greater the number of parameters documented, the more that is revealed about potential antecedents. Because of the impossibility of infinitely documenting a system parameter, written documentation data are considered to be samples of the universe of data that can be potentially derived about the relevant parameters. Hence, the more data obtained, the closer the measure corresponds to dimensions of the actual attribute rather than to a sample of it.

For example, a single health measure, heart rate or pulse, provides a limited portrait of an individual's cardiovascular state. Generally, health care providers measure pulse in 15- to 30-second intervals to derive a baseline rate. However, to obtain more accurate measures they could document heart rate over a 1- to 2-hour period. Although the obtained data would more closely

correspond to a person's baseline pulse on that day, the cost of obtaining the data would not justify the benefits that would be derived from the increased accuracy. Therefore, the relatively brief measures of heart rate provide data that effectively, but not perfectly, measure the parameter of interest.

Collection Frequency and Regularity

The more often a trait is measured, the better the data can reveal changes in measures of the trait. Frequent measures provide a more complete portrait of a parameter than would infrequent measures. For example, people who weigh themselves only once every 5 years would not learn of small weight variations in that period. By contrast, if they weighed themselves 100 times in the 5-year period, they would obtain a more complete picture of their actual weights than possible from a single measure.

Frequent measures of attributes should also be reasonably spaced to reveal variations in the trait over time. Using the same example, weights measured 100 times every 3 weeks, describe weight more accurately over the 5-year period than 100 weights measured in 1 month of that 5-year period. The greater the number of measures of a parameter, and the more equal the intervals between those measures, the greater the value of the obtained data.

Length of Time Since Collected

The closer to the time of the incident or accident in which measures of a parameter are obtained, the closer the measures will correspond to the actual parameter value at the time of the event, which is the period of the investigators' greatest interest. Investigators may find that data obtained after, but close to the time of an incident or accident, are more valuable than data obtained before the event, provided that the experience of the event did not affect the value of the parameter. In this way, a measure of an operator's performance taken 2 days after an accident will likely be more valuable to investigators than a comparable performance measure obtained a year before, so long as the operator's performance did not change as a result of the accident experience or in association with it.

Reliability

Reliability refers to the consistency of measures of a trait. Reliable measures vary little between measurements, while unreliable measures will vary. Using the illustration of weight, if people were to weigh themselves on well-calibrated scales throughout the day, the weights would change little, except for minor diurnal weight fluctuations associated with meals, fluid loss, etc. However, if they were to weigh themselves on several uncalibrated scales in the same period, and those weights varied by several pounds or kilograms, the differences would most likely result from differences in the

scales' accuracy rather than changes in their weights, because variations of that magnitude are rare.

Validity

The relationship between the measurement of a parameter and its actual value is known as validity. The closer a measure of a trait corresponds to the value of that trait, the greater its validity. For example, a test used to select candidates to operate a nuclear reactor should predict how well they would operate the reactor. A vocabulary test that applicants complete to be selected as reactor operators may be a valid measure of verbal achievement, but it would likely be of limited value predicting performance as a reactor operator. The knowledge needed to operate reactors extends well beyond vocabulary knowledge. A more valid measure would directly assess skills needed to operate reactors, developed from closely observing operator tasks.

Changes in Written Documentation

It is not unusual to find that over time the nature of information contained within written documentation changes. Measures of operator traits may change as operators gain experience; alternatively, measurement standards may change as systems evolve. Changes in two elements of written documentation, central tendency and organizational factors, are particularly noteworthy as they may reveal much about the operator and the operator's employer.

Stable Characteristics

Assessments of particular attributes, characteristics, or conditions should reveal what will be referred to as "stable characteristics," traits that tend to remain fairly stable from year to year. Performance appraisals, for example, generally include an assessment of overall job performance, a fairly stable measure over the short term. Someone who performs well one year would be expected to perform well the next. Because of its stability, marked inconsistencies in an operator's overall job performance over time would be cause for additional inquiry.

Investigators of the 1994 accident involving an FAA-operated aircraft used to inspect navigation aids, discussed in Chapter 6, found that the stable characteristics of the pilot in command's performance data contained among his personnel records was positive, with one inconsistency (National Transportation Safety Board, 1994). His supervisor had consistently evaluated the pilot's performance positively, however, 6 months before

the accident he reprimanded the pilot for a performance-related event, a reprimand that was inserted into his performance records.

After interviewing the pilot's peers and supervisors, investigators resolved the inconsistency between his general performance over several years and that described in the reprimand. Co-workers provided a different account of the quality of the pilot's performance than that described in the stable characteristics of the performance appraisal results. Interviewees described instances in which the pilot disregarded safe operating practices, information that corresponded to the gist of the letter of reprimand and his performance at the time of the accident, but not to the stable characteristics of the performance appraisal results. Because the action that the pilot had taken, which resulted in the letter of reprimand, was reported by another pilot, the supervisor was forced to respond to the action. Therefore, the value of the stable characteristics was diminished as the inconsistency was explained.

Organizational Factors

Written documentation may contain data that reveal characteristics of the company as well as the person. In the above-described accident for example, investigators resolved the discrepancy within the captain's personnel records by interviewing the pilot's peers and supervisors. Their comments raised critical issues regarding the performance of the supervisor and the organization in overseeing the pilot and their response to safety-related issues.

Comparing written documentation data of one operator to similar data of other operators in an organization may also give insights into company policies and actions. To illustrate, consider a locomotive engineer whose personnel records shows numerous citations for rule violations in a 5-year period, an individual who may well be a poor performer. However, if the records of other engineers in that railroad contained relatively equivalent infractions over similar intervals, then the engineer's performance would be "average" among other engineers.

Summary

Companies generally maintain data in three types of written documentation, personnel, training, and medical records. The data in these records may provide information about the operator and his or her employer. Driving history, and financial and legal records may also contain information that could help to identify operator-related antecedents to error.

The quantity of information about a trait, the frequency and regularity with which the information was collected, and the reliability and validity of

the measures that provide the data, affect the quality of data in written documentation. Investigators should examine general trends within the data, departures from consistency, relative rate and direction of change, similarity to information in the company records of others, and organizational factors, when reviewing data in written documentation.

APPLYING WRITTEN DOCUMENTATION TO INVESTIGATIONS

PREPARATION

- First identify the information likely to be pertinent to the event, and the most likely sources of that information.
- Identify and locate experts when reviewing unfamiliar information, such as financial and medical data, for assistance in interpreting the data.

MEDICAL INFORMATION

- Examine operator medical records of both company-sponsored medical care and sources independent of the company, if available.
- Document operator visits to health care providers that occurred within the 3 years before the event, results of diagnostic tests and health care provider's diagnoses, treatments, and prescribed and recommended over-the-counter medications.

FAMILY INFORMATION

- Obtain family information if there is reason to believe that the operator experienced family-related difficulties near the time of the event. Obtain law enforcement assistance to obtain access to the information if necessary.

ASSESSING THE DATA

- Note the amount of data available on a given trait, the frequency and regularity of data collection, and the reliability and validity of the data.
- Determine the presence of stable characteristics of the data that pertain to each trait.
- Resolve inconsistencies in the data, generally by interviewing those who can comment on the discrepant information.
- Look for information on the company as well as on the operators within company-maintained documentation.

AFTER REVIEWING THE DATA

- Summarize the major points of the information contained within the written documentation.
- Contact the person familiar with the information if there is still uncertainty about the meaning of some of the information.

References

McFadden, K. L. 1997. Policy improvements for prevention of alcohol misuse by airline pilots. *Human Factors*, 39, 1–8.

National Transportation Safety Board. 1990. *Marine accident report, grounding of U.S. tankship Exxon Valdez on Bligh Reef, Prince William Sound, Near Valdez, Alaska, March 24, 1989.* Report Number: MAR-90-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1994. *Aircraft accident report, controlled flight into terrain, Federal Aviation Administration, Beech Super King Air 300/F, N82, Front Royal, Virginia, October 26, 1993*. Report Number: AAR-94-03. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997. *Railroad accident report, near head-on collision and derailment of two New Jersey Transit commuter trains, near Secaucus, New Jersey, February 9, 1996*. Report Number: RAR-97-01. Washington, DC: National Transportation Safety Board.

Section IV

Issues

13

Maintenance and Inspection

> If some evil genius were given the job of creating an activity guaranteed to produce an abundance of errors, he or she would probably come up with something that involved the frequent removal and replacement of large numbers of varied components, often carried out in cramped and poorly lit spaces with less-than-adequate tools, and usually under severe time pressure.
>
> **Reason and Hobbs, 2003**
> *Managing Maintenance Error*

Introduction

Complex systems need to be maintained to be able to continuously operate in working order because components wear out, cables stretch, bolts loosen, fluids become depleted or dirty, and critical elements fail. Preventive maintenance reduces the likelihood of such occurrences resulting in component failures or malfunctions during system operations. Systems generally undergo two types of maintenance, scheduled and unscheduled. Scheduled maintenance is preventive, intended to inspect and replace components, fluids, belts, etc., before they wear out or fail. Unscheduled maintenance is directed to repair equipment anomalies.

All of the antecedents to error described in these chapters apply to maintenance errors, which may result from antecedents in training, operator team operations, and so on. What distinguishes maintenance errors from the others described here are antecedents unique to maintenance and the manner in which they can affect maintenance operations. To some extent this is because the environment in which maintenance is typically conducted is unique. As Hobbs and Williamson (2003) observe regarding aviation maintenance:

> Aircraft maintenance is performed in an environment that contains many potential error producing conditions. Maintenance workers routinely contend with inadequately designed documentation, time pressures, shift work, and environmental extremes. (p. 187)

Despite the importance of maintenance, until recently researchers paid scant attention to maintenance errors. Exceptions include Boeing Corporation's study of commercial aircraft maintenance errors, and the maintenance error decision aid (or MEDA) they developed. This was designed to help maintenance personnel identify the antecedents to maintenance errors and implement strategies to reduce the likelihood of their reoccurrence (Rankin, Hibit, Allen, and Sargent, 2000). The Federal Aviation Administration has also devoted substantial effort to understand maintenance and inspection errors, greatly enhancing our understanding of maintenance operations. This chapter will examine the maintenance environment and maintenance tasks to explain how antecedents to error in maintenance tasks can occur.

Maintenance Tasks

Depending on the complexity of the system, maintenance may be carried out by one or a team of operators performing numerous, often unrelated tasks. The number of maintenance personnel and the number of tasks they perform depends, of course, on the complexity of the task. Often one team of individuals assigns and describes the task to be done, another team performs the maintenance, and a different one inspects the results of the maintenance to verify its quality. As Ward et al. (2010), referring to maintenance in commerical aviation describe,

> Aircraft maintenance is a highly dynamic and regulated industry characterised, for example, by complex and interdependent systems and technologies, detailed and legally binding task procedures and documentation, highly publicised accident rates and highly regulated management systems to ensure reliability, efficiency and safety at all times (Corrigan 2002). Task analysis has revealed aircraft maintenance activity to be a complex socio-technical system requiring sustained coordination, communication and cooperation between different work groups and teams including aircraft maintenance engineers (AMEs), crew managers, inspectors and hangar managers, various other subsystems, such as planning and commercial, stores, quality and engineering and external bodies, such as the regulators, the manufacturer, the customer and the airline, in order to ensure efficient and effective operations. (p. 248)

Because maintenance technicians often receive limited or no immediate feedback on the quality of the tasks they complete, maintenance errors, such as using an incorrectly sized bolt or filling a component with the wrong fluid, may not be discovered until after the repaired or maintained item has been reintroduced into service. Hobbs and Kanki (2008) surveyed aviation maintenance errors reported to NASA's Aviation Safety Reporting System.

The most common errors they identified were an omitted action, that is, an action that should have been but was not carried out, inaccurate or incorrect documentation, or an incorrect part installed. Further, they found an association between parts of the airplane and the types of errors associated with it. Particular parts or systems tended to be associated with certain types of errors and error antecedents.

Drury (1998) contends that maintenance and inspection tasks consist fundamentally of a handful of discrete steps, in which technicians primarily interpret and diagnose, act (i.e., repair, replace, or inspect), and evaluate or inspect the maintenance action. Antonovsky, Pollock, and Straker (2014) describe the cognitive tasks involved in maintenance activities, tasks that largely fall into Drury's interpret and diagnose, and evaluate categories.

> Problem solving in maintenance relies on correctly determining the source of a fault, deciding on the most efficient means of correction, and applying the solution effectively. All of these cognitive processes are required for successful corrective maintenance, and a logical flaw in any of these leaves the fault unresolved. (p. 315)

The type of maintenance error an investigator may look for depends largely on which of the steps Drury identified, and to which particular step the maintenance action belonged. Diagnosis errors are different from maintenance action errors, and the antecedents will likely be different as well. Further, unlike tasks that system operators typically perform, maintenance tasks offer multiple opportunities to error that may be independent of the task itself. For example, unlike tasks that other system operators conduct, maintenance tasks may vary from day to day, affording maintenance personnel little opportunity that other operators would have to become well-versed in a few tasks, performed repeatedly as part of the job. In addition, because maintenance tasks are often initiated by someone or something different from the person or persons performing the task, opportunities for communication errors between the dissemination of maintenance instructions and their receipt and comprehension by the person performing the task offer opportunities for error different from those of system operators. Thus, the first step in identifying antecedents to maintenance error is to examine the nature of the communication to the technician who performed the task to assess how well he or she understood the task to be completed, and his or her understanding of the process needed to complete the task.

Interpret and Diagnose

Communicating the task to be performed. Maintenance technicians typically initiate a task after receiving either verbal or written instructions to do so. The instructions can describe an anomaly or present a maintenance task and list the actions that need to be performed to complete it. In response to an

anomaly the maintenance specialist will diagnose the nature of the anomaly and select an appropriate action based on that diagnosis. Because the initial reports of anomalies are often provided by those who interact with rather than maintain the system, the accounts may be insufficiently precise to enable maintenance technicians to readily diagnose the anomalies. Those who report the anomalies may be unaware of the needs of the technician, they may be in a rush to complete writing up the maintenance anomalies, or they may simply be describing the anomaly from a user's perspective rather than from that of the person who will repair it. Munro, Kanki, and Jordan (2008) describe many barriers to effective communication between pilots and maintenance technicians in transmitting information regarding anomalies from the operators to the maintenance technicians.

By contrast, scheduled maintenance tasks are often generated from a data base of task schedules, with computer-generated steps from a central source, such as a general maintenance manual, that describe the steps needed to complete the task. Drury (1998) found that printed instructions given to maintenance technicians occasionally contain flaws that can lead to maintenance errors. These include insufficiently sized font and incomplete or poorly written instructions that lead maintenance technicians to misunderstand or not fully understand the nature of the task they are to perform.

Because some maintenance tasks are performed over extended periods of time, maintenance personnel may not complete them within their duty periods. In that event they will need to brief personnel in the subsequent shift on the tasks they had completed and the tasks that remain. Those receiving the information will then apply the instructions they received to the task to be performed. Again, deficiencies in either communicating or comprehending the instructions or in applying them to the task may lead to errors. Ambiguity in the verbal description of the system condition or the receiver's misunderstanding of the information can also lead to error. Yet verbal instructions are common, particularly if tasks were partially completed.

At the same time maintenance tasks can offer opportunities to mitigate errors that are typically absent in complex systems. Maintenance technicians can, when faced with a challenging situation, stop their action and reconsider it, or consult with a colleague or supervisor, without having to continue overseeing system operations (Hobbs and Williamson, 2002). The ability to focus on a situation exclusively without having to simultaneously monitor other aspects of system operations considerably eases some of the pressures maintenance technicians face in performing their jobs.

Antonovsky, Pollock, and Straker (2014), in a study of maintenance in the offshore petroleum industry, found that 95% of the maintenance errors reported by maintenance supervisors were the result of either poor communication of maintenance information, or poor problem-solving (i.e., diagnosis). The role of effective communication and interpretation of maintenance information is critical to effective maintenance, and an antecedent to error

when such communication and interpretation is poor. To perform this step properly a maintenance technician must know the type of anomaly the operator described and its possible causes, or fully understand the written account of the maintenance to be performed. In addition, he or she should be sufficiently familiar with the system and its components and subsystems to apply the description of the anomaly or maintenance actions to the component or subsystem in question.

Further, some organizations do not perform their own maintenance but contract third parties to conduct both their scheduled and nonscheduled maintenance on their behalf. These third-party maintenance contractors are independent of the operating organizations, and as a result the potential for maintenance errors increases from the increased oversight distance between the organization contracting and overseeing the maintenance and the one that is conducting the maintenance. Drury, Guy, and Wenner (2010) examined the potential for error arising from outsourcing maintenance to third parties. They found that when third parties are contracted to maintain the systems of others, additional opportunities for errors in communications are introduced as maintenance personnel communicate through their own supervisors, who then communicate with the operating company and report back to the personnel, thus increasing the layers of communication between those who maintain systems and those who operate them, therefore increasing opportunities for communication errors.

Most regulators consider the operating company to be ultimately responsible for the maintenance performed on its system, regardless of where the maintenance is conducted. Regulators may, depending on the industry, establish a floor of minimally acceptable maintenance standards and personnel qualifications for the companies they oversee. Nevertheless, increasing the oversight distance between the company operating the system and the company maintaining it allows antecedents to error to be introduced, a result of the maintenance organization's unfamiliarity with a company's standards and how the standards are expected to be applied. In addition, third-party contractors may have inventory systems for parts that are different from that of the company and thus will need to merge its systems with that of the company or learn to use another company's systems. Third-party maintenance contractors may also be more likely to misinterpret a company's instructions than would those working directly for that company.

Third-party maintenance organizations may themselves contract out the hiring of maintenance personnel to other companies, as was seen in the DC-9 accident in the Florida Everglades described in Chapter 10 (National Transportation Safety Board, 1997). Maintenance personnel from these organizations can be expected to have little loyalty to the organization for who they perform the maintenance, and should not be expected to be familiar with the operating organization's way of communicating and conducting maintenance, as would be expected of those in the direct employ of the operating company.

Act

After interpreting and diagnosing, technicians generally perform one or more of the following actions, each of which calls for different skills

- Removing a component and replacing it with a repaired, reassembled, or new component
- Repairing a component
- Disassembling and reassembling a component
- Disconnecting and reconnecting a component
- Emptying and replacing fluids

Because there are numerous opportunities for error in reinstalling and reconnecting components and in replacing fluids, these steps can be prone to error.

Reason (1997) suggests that because of the numerous ways that components can be incorrectly reassembled and reconnected, or the ways that incorrect types or quantities of fluids can be used, in contrast to the single way that they can be removed or disassembled, maintenance personnel are more likely to commit errors when completing these tasks than when performing other maintenance tasks. Reassembling components not only calls for using the correct component, but also the correct attachment parts, for example, screws and bolts, in the correct amount, placed in the correct location, with the correct torque or tension. Errors can occur in any one of the maintenance activities.

This maintenance step, does however, require little cognitive effort. Hobbs and Williamson (2002) applied Rasmussen's (1983) model of skill-, rule-, and knowledge-based performance to maintenance tasks and found, in a study of errors of aviation mechanics, that the fewest errors were considered to involve skill-based tasks. Such tasks, whether maintenance or other type, become mastered when people perform them multiple times. Over time the tasks can be conducted with little conscious thought, and hence with fewer errors. By contrast, they found that maintenance supervisors spent considerably more of their time overseeing the work of others, and hence on knowledge-based tasks, which required a higher level of cognitive effort than action tasks, and thus were more prone to error.

Evaluate

After receiving instructions, maintenance personnel inspect components and may observe the operation of the system to diagnose the anomaly or evaluate the type of maintenance actions needed. Evaluation and inspection are subject to distinctive antecedents and, depending on the procedures, the setting, and the type of task performed, the rate of detecting flaws

may vary. For example, Leach and Morris (1998), who studied maintenance actions in an unusual environment, welds performed underwater, found that inspectors failed to detect defects at a rate well above the accepted tolerance level, with no correlation between experience of the inspector and error rate. Ostrom and Wilhelmsen (2008) found considerable errors in technicians' abilities to detect dents in a simulated "real world" setting in which flashlight lighting was used with dirt and grime covering the area to be examined, compared to ideal conditions with ideal lighting and little dirt and grime. It can be seen that, as a result of the unique settings in which maintenance personnel search for flaws, inspection tasks are prone to error, regardless of the experience of the particular person conducting the inspection.

Often the defects that inspectors are asked to identify are barely perceptible. Because many of the components that they inspect are flawless, inspectors may have little or no history of detecting flaws and, as important, little or no expectation of finding them. Their expectancies could affect their detection of flaws since previous experience helps to guide visual searches. Previous experience can help inspectors locate and identify flaws, but it could also lead to potential error-inducing expectancies when flaws had not been encountered previously. In general, because most maintenance tasks are performed without error, inspectors may become habituated to expect satisfactory results when examining the products of the maintenance activities of others, thus degrading their ability to locate flaws.

Components may lack indices that can assist inspectors in searching all the critical areas they are examining. Specialized tools have been designed to highlight defects in some types of inspections; however, the effectiveness of these tools is largely dependent on the user's expertise. Here again, previous experience in detecting flaws can increase an inspector's ability to detect subsequent flaws. Further, because these tools can place considerable demands on inspectors' vigilance, over extended periods of time their visual searching and monitoring skills will degrade.

Failure to detect flaws has led to accidents. An inspector failed to detect a flaw in a jet engine disc during a scheduled engine inspection. The flaw continued to grow and propagate as the engine was subject to repeated operating cycles. Nine months after an inspector had looked for and missed a flaw using an instrument designed to enhance the conspicuity of flaws, the part disintegrated as the airplane was about to take off, leading to the death of two passengers (National Transportation Safety Board, 1998). Investigators described the difficulties the inspector encountered in searching for the defect,

> To detect the crack on the aft-face of the hub, the inspector would have had to first detect a bright fluorescent green indication (if there was such an indication) against a dark purple background. To detect the indication,

> the inspector would have had to systematically direct his gaze across all surfaces of the hub. However, systematic visual search is difficult and vulnerable to human error. Research on visual inspection of airframe components, for example, has demonstrated that inspectors miss cracks above the threshold for detection at times because they fail to scan an area of a component. It is also possible that the inspector detected an indication at the location of the crack but forgot to diagnose, or reinspect, the location. [Moreover,] a low expectation of finding a crack might also have decreased the inspector's vigilance. Further, research on vigilance suggests that performance decreases with increasing inspection time. (pp. 63 and 64)

The Maintenance Environment

Unlike operator control stations in complex systems, which are often climate controlled, well lit, and quiet, maintenance environments are susceptible to noise, temperature variations, and poor illumination, among other challenging conditions. The maintenance environment itself is far more conducive to errors than are typical operational environments as they are often exposed to large-scale temperature variations, with considerable, intrusive background noise (Bosley et al., 2000). In addition, unlike many system enviornments where operator controls are either illuminated when needed or provided with sufficient background illumination for operator use, maintenance environments may lack proper illumination.

Lighting

The environment in which maintenance is conducted is often provided with external light that is designed to illuminate the general work environment and not the areas on which maintenance personnel focus. Illumination shortcomings can be present in confined or enclosed spaces, or in open spaces where general overhead lighting is the primary source of illumination. Technicians could employ portable lighting fixtures to compensate for these deficiencies; however, using hand held fixtures requires technicians to dedicate one hand to holding the fixture, leaving only the other hand for the maintenance task itself. If hands-free operation is not possible, the technician's ability to work effectively will be impeded, either because of constraints from the use of only one hand, or because of the poor illumination, leading to a maintenance or inspection error. However, the availability of relatively inexpensive wearable, lightweight, battery operated white LED (light-emitting diode) lights has mitigated, to some extent, the lighting shortcomings of many maintenance environments.

Noise

Maintenance environments can be quite noisy, many are not sound-controlled and ambient noise from ongoing activities may interfere with technicians' work. As discussed in Chapter 4, sounds can distract operators and interfere with their job performance. If sufficiently loud, noise can also limit technicians' ability to converse or to hear verbal instructions. Although maintenance personnel can wear protective devices to limit the adverse effects of noise, these devices can interfere with their duties if they are uncomfortable, hinder conversation, or restrict movement.

Environment

Technicians may be exposed to wide variations in temperature and humidity because maintenance tasks are often performed outdoors or in environments that are not climate controlled. People perform effectively at a fairly narrow temperature and humidity range. Although cultural and geographical factors affect sensitivity, research has demonstrated that as temperatures extend beyond a fairly narrow range, from about 60°F or 15°C to about 90°F or 35°C (e.g., Ellis, 1982; van Orden et al., 1996; Wyon et al., 1996; Bosley et al., 2000), ambient temperature increasingly becomes a stressor that adversely affects operator performance. Humidity increases sensitivity to temperature and exacerbates its effects. The higher the relative humidity, the narrower the temperature range in which people can work without being affected by the temperature-related stress.

Other potentially adverse environmental factors can also degrade performance in the maintenance environment. These include pollution, such as from smoke, dust, or allergens and strong odors and vibrations from the equipment or its operating environment.

Accessibility

Tight quarters, exposed wires, chemicals, moving objects, protruding or sharp objects, the lack of protective barriers high above the ground, and other hazards may be present in the maintenance environment. These hazards, and technicians' concern for and efforts directed at self-protection, can degrade performance. Although they can wear protective equipment in hazardous conditions, the protection itself may interfere with technicians' mobility and thus lead to performance errors. To illustrate, heavy gloves that protect operators from sharp objects also restrict their dexterity.

Features of the maintenance environment played a role in technicians' errors in an incident in which one of the four engines on a Boeing 747 became partially detached from its pylon—the component that attaches the engine to the wing—upon landing (National Transportation Safety Board, 1994). No one was injured in the accident, but had the engine fallen off while the

airplane was in flight the safety of flight could have become compromised. Investigators found that the pin that connected the engine to the pylon was missing. About a week before the incident a mechanic who had performed maintenance on the pylon failed to reinstall the pin. Following the mechanic's actions an inspector examined the pylon, but he failed to notice the missing pin. These maintenance and inspection errors led to the incident.

Investigators found that the relative inaccessibility and poor illumination of the critical component played a part in the errors. The inspector had to lean about 30° to the side, from scaffolding without barriers, to inspect the component. The scaffolding itself was located about 30 feet or 10 meters above a concrete floor. As investigators report (National Transportation Safety Board, 1994),

> The combination of location of the scaffolding (at a level just below the underside of the wing that forced him [the inspector] into unusual and uncomfortable physical positions) and inadequate lighting from the base of the scaffolding up toward the pylon, hampered his inspection efforts. Moreover, portable fluorescent lights that had been placed along the floor of the scaffolding illuminated the underside of the pylon. These lights had previously been covered with the residue of numerous paint applications that diminished their brightness. (p. 30)

Tools and Parts

Poorly designed tools, parts, and equipment can degrade maintenance quality and lead to error. They can be awkward to hold, difficult to use, block the technician's view of the maintenance action, or present technicians with any of a number of difficulties. Reason and Hobbs (2003) referring to "among the most influential local conditions influencing work quality," note that poorly designed tools and misidentified or missing parts can play critical roles in maintenance errors (p. 67).

Poorly labeled or poorly designed parts may be used incorrectly or may be applied to the incorrect component. Many parts are relatively indistinguishable, differing in seemingly imperceptible ways, yet the use of even "slightly" different parts can lead to an accident. In addition, since those who store parts do not generally perform the maintenance using those parts, they may not appreciate the needs of those who do. They may insufficiently differentiate among parts when storing them, or fail to label them clearly, actions that can lead technicians to select incorrect parts for the critical tasks.

Time Pressure

Although many tasks that operators perform in complex systems are carried out under some time pressure, the pressures on maintenance technicians may be considerable. In many systems, operations are stopped or slowed

at regular intervals, providing intervals for scheduled maintenance to be performed without adversely affecting operations. For example, some urban mass transit systems shut down in the late night/early morning hours, allowing maintenance to be performed without interrupting system operations, as would be the case if performed in the daytime. However, those systems resume operations at set times and maintenance activities must be completed within the required time frames to allow operations to resume. Technicians conducting maintenance in those times are aware that they must complete them within the allotted time. Inflexibility in the times to complete operations can pressure personnel to hurry through tasks if they have encountered unexpected problems or the tasks took longer than expected.

The pressure to complete tasks can lead technicians to skips steps, or to conduct hurried maintenance or inspection activities, thereby increasing opportunities for error. This was the case, for example, in a maintenance-related accident that occurred when a windscreen of a BAC 1-11 aircraft blew out as the airplane was climbing, because the maintenance technician who conducted a scheduled maintenance task the night before the accident used bolts slightly smaller than required to retain the windscreen in place (Air Accidents Investigation Branch, 1992). The maintenance was performed at night, the shift was ending, and the maintenance crew was short-staffed. A supervisor conducted the maintenance himself rather than assign it to a subordinate in order to expedite its completion, to increase the likelihood that the airplane would be returned to service in the morning. However, he inadvertently used incorrectly sized bolts to retain the windscreen. As the airplane climbed, the ambient pressure outside the airplane decreased, the cockpit and cabin pressure remained the same, and the differential pressure on the windscreen increased to the point that it could not be retained in place. The error occurred from a variety of antecedents; the supervisor knew that the airplane needed to return the service, he was under pressure to obtain the parts (the bolts) needed to complete the task, he did not recognize that he had obtained bolts that were slightly smaller than the parts needed for the task, and upon completion his work was not inspected by a different inspector.

Case Study

In January 2003 a Raytheon (Beechcraft) 1900D, with 19 passengers and two pilots onboard, crashed shortly after takeoff from Charlotte, North Carolina, killing all 21 onboard (National Transportation Safety Board, 2004). As the aircraft lifted off the runway and began its climb, its nose continued to pitch upward but the pilots were unable to decrease the pitch, despite their

continued efforts. Just over a minute after takeoff the airplane crashed into a maintenance hangar on the airport property.

Two nights before the accident maintenance personnel performed scheduled maintenance to check and, if necessary, readjust the tension of cables connecting the pilots' control columns to the elevators, the control surfaces that lower or raise the aircraft tail, to increase or decrease its pitch in flight. The airline had contracted with a third party to perform maintenance on its aircraft. At the facility in which the maintenance was performed that contractor had then contracted with another company to provide it with the technicians who would actually perform the aircraft maintenance.

The maintenance personnel who performed the critical maintenance actions were the quality assurance technician, who inspected the completed maintenance actions, the site facility manager, who represented the company that maintained the aircraft, the maintenance foreman who oversaw the maintenance task assignments, the technician who worked on the airplane, and the airline's site manager, who was responsible for ensuring that the maintenance was carried out in accordance with the airline's Federal Aviation Administration-accepted maintenance program. The airline's representative, employed by the airline, and the site supervisor, employed by the company that maintained the aircraft, both worked at the maintenance facility during daytime hours, Monday through Friday. The maintenance personnel, who worked for the company that supplied the maintenance personnel, worked at nights.

Investigators determined that the actual weight of the passengers and their baggage exceeded that of the average passenger weight that the airline had used to make weight and balance determinations for their aircraft, and as a result the passenger and baggage weight distribution was further aft than it should have been, thereby making the airplane tail heavy and prone to pitching up. Ordinarily pilots can counter this by lowering the nose through the airplane's control column, but they were unable to do so on this flight and the airplane's pitch continued to increase until the airplane crashed. The airline, like most, had used an average passenger and baggage weight that the Federal Aviation Administration had approved some years before. However, since the weight calculations were first developed the weight of the average American, as well as that of others around the world, increased and the weights that the Federal Aviation Administration had approved for the average American passenger were, in effect, no longer valid. Further, the average passenger gender distribution was based on a mix of 60% male and 40% female passengers whereas on the accident flight 16 males and three female passengers were onboard. After the accident, at the request of the Federal Aviation Administration, several airlines tallied the actual weights of their passengers over a 3-day period. They found that the average passenger weight that airlines had been using was more than 10% below than that used in the Federal Aviation Administration approved average weights,

and the baggage weights were found to have exceeded the average baggage weights by about a third.

The aircraft's control column's forward deflection was found to have been limited to about 7° rather than the 14°–15° specified in the airline's maintenance manual. Investigators learned that a downward deflection of about 9° was needed to safely fly the airplane with the aft center of gravity loading it had at the time of the accident. The aft weight distribution that led to the airplane's pitch up after takeoff should not, by itself, have prevented the pilots from controlling the airplane and the pilots' words heard on the cockpit voice recorder indicated that they were actively trying to lower the nose.

Investigators found multiple errors and error antecedents in the maintenance conducted two nights before the flight, which, together with the aft center of gravity, caused the forward control column limitation that led to the accident. The maintenance technician who worked on the cable tension had omitted several steps in adjusting the cable tension. In particular, he did not calibrate the tension after he had readjusted it. Further, the quality assurance inspector was aware of and approved the technician's omission of the step; neither believed that all the steps called for to adjust the tension were necessary, despite the steps being explicitly listed in the maintenance manual, and therefore required. Had the required maintenance actions been carried out, the actual column deflection would have been conducted, the cable tension calibrated, and the incorrect cable tension recognized.

The inspector had been employed by the maintenance contractor about 6 months before the accident, and the maintenance technician, employed by the company that provided maintenance personnel to the maintenance contractor, about 2 months before the accident. In this respect, their tenure with that company was generally consistent with that of their colleagues, the average length of service being about 3 months. Moreover, investigators found that the absence of either the airline representative or the maintenance contractor's site facility manager at night, when much of the critical maintenance was performed, resulted in the absence of someone familiar with company maintenance procedures, a person who could have informed them of the need to follow all the required steps of the maintenance procedures when a technician had sought to omit required maintenance actions. Their absence also resulted in their not observing much of the maintenance that was conducted on company aircraft, and not noticing the extent to which steps listed in the maintenance manual were not followed.

Investigators also learned that the technician who performed the cable maintenance had not performed that action on the model of airplane involved in the accident, although he had done so on a different type of aircraft. Training on maintenance tasks at the facility was conducted through on the job training or OJT. The quality assurance inspector, who provided the OJT to the maintenance technician on this task, told investigators that he did not believe that he needed to closely supervise the technician because of the

technician's previous experience of that task, even though it was on a type of aircraft that had slight resemblance to the airplane under maintenance.

Investigators also found that the written instructions regarding the cable adjustment procedures were located in two separate documents. One step was documented in a second manual, thereby calling for technicians, during the procedure, to access a second document in addition to the one guiding them in the tasks. By forcing the technicians, while following the maintenance steps, to stop their work, consult a second manual, follow that step and then return to the steps in the other manual, an additional error antecedent was introduced into the process. Finally, after the maintenance was conducted, its quality was assessed by the quality assurance inspector, the person who had approved omitting the critical maintenance steps. Although applicable regulations did not prohibit inspectors from overseeing or training personnel performing maintenance tasks and then inspecting the completion of those tasks, investigators criticized the maintenance contractor's doing so, and the airline's representative for not recognizing and prohibiting this practice. As investigators wrote (National Transportation Safety Board, 2004),

> The inspectors cannot properly fulfill their RII [required inspection item-tasks that require separate inspection] responsibilities in such a situation. The purpose of an RII inspection is to provide "a second set of eyes" to ensure that any error made in performing maintenance work is detected and corrected before an airplane is returned to service. (p. 107)

Thus, a simple maintenance error, incorrectly adjusting cable tension, led to misrigged cables that prevented the pilots from recovering from an otherwise correctable airplane pitch up. Because the passenger and baggage weights and distribution were inaccurate, the airplane was loaded tail heavy, causing the pitch up. The error in rigging the cables was committed by an ill-trained technician who had little experience with the airplane type or with the airline for whom he was performing maintenance actions. He was employed neither by the airline nor by the maintenance third party the airline had retained to conduct its maintenance but by a contractor that provided maintenance personnel to the maintenance third party. Cumbersome written instructions describing the maintenance actions may have played a role in the mechanic's omission and the inspector's approval of the omission and subsequent failure to recognize its consequences, the misrigged cables.

Summary

Maintenance largely involves three critical acts, recognizing and understanding the maintenance to be performed, carrying out the maintenance,

and evaluating or inspecting the effectiveness of the action taken. Errors can take place even before the maintenance task itself is performed, in the instructions given to or received by the maintenance specialist, as well as because of aspects of the maintenance environment, the task itself, or the tools and parts used.

The maintenance environment differs substantially from those of most system control stations in complex systems. The environment may be subject to temperature extremes, poor illumination, distracting ambient noise, and difficult to access components.

Flaws or defects that inspectors examine may be relatively inconspicuous and difficult to detect. Inspectors may use devices to enhance flaw and defect conspicuity, but after extended visual inspection their effectiveness in detecting flaws will deteriorate. Previous experience detecting flaws will affect inspectors' expectations and the likelihood of finding flaws in subsequent inspections.

DOCUMENTING MAINTENANCE ANTECEDENTS

MAINTENANCE AND INSPECTION

- If there is reason to believe that it was uncomfortably hot or cold at the time the maintenance was performed, measure the temperature and humidity several times a day over a period of several days, as close as possible to the time of the accident, and use the average temperature and humidity if the information is not available.
- Identify company deadlines to complete the required tasks.
- Evaluate the nature of written or verbal maintenance instructions, information on equipment, tools, and parts used, difficulties in their use, company training, and other relevant information by interviewing those who performed the critical maintenance, or were performing maintenance nearby at the time.
- Measure the illumination of the critical component and document the source of the light, its power, preferably in foot or meter candles, the area being illuminated, and the location of blind spots, dark areas, or other deficiencies.
- Measure the ambient sound level at a time close to the time of the event if sound recordings at the time of the accident are not available.
- Obtain data concerning the work of the maintenance personnel at the time of the event from security cameras, audio recorders, and other devices.

- Determine accessibility to the component of interest from the location at which the maintenance technician performed the maintenance or inspection.
- Document material or components that blocked access to a component, and any exposed wiring, hazardous chemicals, or other potentially dangerous material in and around the work area.
- Determine the number of tasks the technician was scheduled to perform around the time the critical maintenance was carried out.
- Assess the time remaining between the completion of the required maintenance action and the end of the shift and the time when the component was to be reentered into service.

MAINTENANCE

- Measure differences among the dimensions of tools and parts used in the maintenance task and those of tools and parts approved for the task.
- Determine the availability of documentation on the correct tools or parts to be used and impediments to accessing the information.
- Examine the accessibility of the correct parts, and document the type and availability of information available to operators that described the parts to be used.
- Note the distance between the location of the parts and the location of the component that was maintained.

INSPECTION

- Determine the amount of time the inspector devoted to inspection.
- Note the number of inspections of the particular component the inspector had carried out previously, and the number of times the inspector found flaws, defects, or incomplete maintenance.
- Measure the size of the flaw if possible, and document features that distinguish a flawless component from a flawed one, or a completed maintenance task from an incomplete one.

THE TECHNICIAN

- Obtain medical, financial, and personal information, as appropriate, to document potential operator antecedents that could pertain to the technicians.

- Document the technician's visual acuity, particularly for near vision. Ask the maintenance technician to obtain a visual examination, if possible, if a year or more has elapsed since the inspector's vision was last assessed.
- Determine whether the operator wore corrective lenses at the time of the event, and the extent to which the lenses corrected for any visual impairment.

References

Air Accidents Investigation Branch. 1992. *Report on the accident to Boeing 737-400, G-OBME, near Kegworth, Leicestershire, on 8 January, 1989*. Aircraft Accident Report No. 4/90 (EW/C1095). London: Department of Transport.

Antonovsky, A., Pollock, C., and Straker, L. 2014. Identification of the human factors contributing to maintenance failures in a petroleum operation. *Human Factors*, 56, 306–321.

Bosley, G. C., Miller, R. M., and Watson, J. 2000. *Evaluation of aviation maintenance working environments, fatigue and maintenance errors/accidents*. Federal Aviation Administration, Office of Aviation Medicine, Washington, DC.

Drury, C. G. 1998. Human factors in aviation maintenance. In D. J. Garland, J. A. Wise, and V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 591–606). Mahwah, NJ: Erlbaum.

Drury, C. G., Guy, K. P., and Wenner, C. A. 2008. Outsourcing aviation maintenance: Human factors implications, specifically for communications. *International Journal of Aviation Psychology*, 20, 124–143.

Ellis, H. D. 1982. The effects of cold on the performance of serial choice reaction time and various discrete tasks. *Human Factors*, 24, 589–598.

Hobbs, A. and Kanki, B. G. 2008. Patterns of error in confidential maintenance incident reports. *International Journal of Aviation Psychology*, 18, 5–16.

Hobbs, A. and Williamson, A. 2002. Skills, rules and knowledge in aircraft maintenance: Errors in context. *Ergonomics*, 45, 290–308.

Hobbs, A. and Williamson, A. 2003. Associations between errors and contributing factors in aircraft maintenance. *Human Factors*, 45, 186–201.

Leach, J. and Morris, P. E. 1998. Cognitive factors in the close visual and magnetic particle inspections of welds underwater. *Human Factors*, 40, 187–197.

Munro, P. A., Kanki, B. G., and Jordan, K. 2008. Beyond "inop": Logbook communication between airline pilots and mechanics. *International Journal of Aviation Psychology*, 18, 86–103.

National Transportation Safety Board. 1994. *Special investigation report, maintenance anomaly resulting in dragged engine during landing rollout, Northwest Airlines flight 18, Boeing 747-251b, N637US, New Tokyo International Airport, Narita, Japan, March 1, 1994*. Report Number: SIR-94-02. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997. *Aircraft accident report, in-flight fire and impact with terrain, ValuJet Airlines, flight 592, DC-9-32, N904VJ, Everglades, Near Miami, Florida, May 11, 1996*. Report Number: AAR-97-06. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1998. *Aircraft accident report, uncontained engine failure, Delta Airlines flight 1288, McDonnell Douglas MD-88, N927DA, Pensacola, Florida, July 6, 1996*. Report Number: AAR-98-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2004. *Aircraft accident report, loss of pitch control during takeoff, Air Midwest Flight 5481, Raytheon (Beechcraft) 1900D, N233YV, Charlotte, North Carolina, January 28, 2003*. Report Number AAR-04-01. Washington, DC: National Transportation Safety Board.

Ostrom, L. T. and Wilhelmsen, C. A. 2008. Developing risk models for aviation maintenance and inspection. *International Journal of Aviation Psychology*, 18, 30–42.

Rankin, W., Hibit, R., Allen, J., and Sargent, R. 2000. Development and evaluation of the Maintenance Error Decision Aid (MEDA) process. *International Journal of Industrial Ergonomics*, 26, 261–276.

Rasmussen, J. 1983. Skill, rules, and knowledge; Signals, signs and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man and Cybernetics*, 13, 257–266.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Reason, J. T. and Hobbs, A. 2003. *Managing maintenance error*. Aldershot, England: Ashgate.

van Orden, K. F., Benoit, S. L., and Osga, G. A. 1996. Effects of cold air stress on the performance of a command and control task. *Human Factors*, 38, 130–141.

Ward, M., McDonald, N., Morrison, R., Gaynor, D., and Nugent, T. 2010. A performance improvement case study in aircraft maintenance and its implications for hazard identification. *Ergonomics*, 53, 247–267.

Wyon, D. P., Wyon, I., and Norin, F. 1996. Effects of moderate heat stress on driver vigilance in a moving vehicle. *Ergonomics*, 39, 61–75.

14

Situation Awareness and Decision Making

> The impetus of existing plans is always stronger than the impulse to change.
>
> **Tuchman, 1962**
> *The Guns of August*

Introduction

Throughout history poor decision making has led to undesired outcomes. In the first days of World War I, for example, the military commanders, and the heads of state and government of several countries made decisions that, that in hindsight led to disastrous consequences (Tuchman, 1962; Clark, 2012). In the face of overwhelming evidence that their initial plans needed to be revised in the light of battlefield conditions, they refused to do so, decisions that ultimately led to their countries' defeat.

In complex systems decision-making errors have led to accidents. These errors often result from deficiencies in operator situation awareness. Because of the importance of situation awareness to decision making, and the importance of decision making to system safety, investigators need to understand both to effectively investigate error. In particular, factors affecting situation awareness, the relationship of situation awareness to operator decision making, and the effects of deficient decision making on operator errors, need to be examined to properly understand decision making and decision-making errors. This chapter will review situation awareness and decision making, and discuss the types of data needed to assess decision making when conducting error investigations.

Situation Assessment and Situation Awareness

Situation awareness has, in recent years, become a widely used term in complex systems. Manufacturers have promoted equipment by its ability to enhance situation awareness, and managers have communicated information for the sake of their operators' situation awareness. Byrne (2015) attributes this wide use of the term to its ease of being understood. As he describes (2015)

> SA [Situation Awareness] is an intuitive and intrinsically satisfying construct that is applicable to both understanding and enhancing human performance in applied environments. SA also serves as a great orienting term to aid in communication about human performance. That is, when used in either conversation or writing, it immediately alerts the recipient to the general area of discussion forthcoming. Whether referenced by an operator learning ways to optimize individual performance or by a human performance analyst providing insights into what factors may have led to breakdowns in performance, use of the term SA helps to focus discussion. (p. 85)

However, the term has also become misused. van Winsen and Dekker (2015) argue that situation awareness has become so overused that it has taken on a meaning away from its initial derivation. As they write (van Winsen and Dekker, 2015)

> The wide use of SA has not only reinforced its status—the more it was used, the greater the consensus authority on using it—but also driven a gradual move away from its original purpose. It has offered new normative standards for behavior: Pilots now describe themselves as good pilots when they are situationally aware, when their decisions are informed by "good SA." Soon after its conception, SA started to appear in accident investigation reports, where it was given great causal power to explain accidents… (p. 53)

van Winsen and Dekker's observation that situation awareness has appeared in accident investigation reports is accurate. However, without describing either how situation awareness was lost or the aspects of situation awareness that were lost or never attained, merely by attributing an error to a loss of situation awareness has not enhanced the understanding of error or explained the actual nature of the critical error or errors. The loss of situation awareness or the failure to gain situation awareness is a critical factor in errors that can lead to accidents, but without describing the antecedents to the loss or absence of situation awareness, or describing how it was lost or not attained, the investigator has not explained how the error came about.

To be able to fully describe the nature of the absence or loss of operator situation awareness, investigators must understand the concept and its application to complex systems. Situation awareness is, first and foremost, the product of situation assessment (Endsley, 2015), while situation assessment is the process of acquiring data or information to enable one to understand or obtain a mental picture of the immediate environment. Situation awareness is the product of situation assessment, a person's understanding or mental picture of his or her immediate environment. Situation assessment and situation awareness are closely related; at any point in time the two are identical.

Endsley (1995) lists three elements that form situation awareness: (1) perceiving the status, attributes, and dynamics of relevant elements in the environment, referred to as Level 1 situation awareness, (2) comprehending the significance of these elements, Level 2 situation awareness, and (3) projecting current assessment to future status, or Level 3 situation awareness. An operator would obtain situation awareness after receiving critical system-related information, understanding it, and using the information to predict the near term system state. Endsley (1995, 2000) argues that situation awareness is based upon elements of both operators and equipment, suggestive of operator and equipment antecedents discussed previously. As we will see, several factors can lead to the inability to obtain situation awareness or to lose it. Perhaps most critical for our purposes is the inability to predict the near-term operational environment. It is not enough to know what is going on in the environment in which an operator is working, he or she must also be able to accurately predict the near-term system state as well.

For our purposes, applying Endsley's concept of situation awareness to complex systems, situation awareness refers to the operator's understanding of what the system is doing, and what it will be doing in the short run. If the operator is an airline pilot, with situation awareness he or she should know where the airplane is, the type of weather it is encountering, and where the airplane will be and what type of weather it will be encountering in the near term. Pilots who don't know where they are, or who don't know how close they are to terrain, have either lost situation awareness with regard to their position or have failed to obtain it. As can be seen, because the environments in which complex systems operate can be considerable, situation awareness should be described in terms of the particular aspect of the environment to which one is referring.

Unless an operator is unskilled, situation awareness is rarely lost when operations are routine. However, when operations are disrupted, something unexpected arises, or routine operations are changed, they may face occasions where they have to quickly interpret the change, diagnose the problem, or recalculate the effects of the change on near-term operations. In circumstances such as these, operators, even skilled ones, can lose situation awareness.

To understand situation awareness, it is necessary to understand factors that influence each of the levels of situation awareness described. One relates to temporal factors, that is, the amount of time the operator has available to

understand the situation being encountered The more time an operator has available to assess a situation, the greater the likelihood that he or she will obtain situation awareness about that situation. Conversely, as the amount of time decreases, the less likely the operator will be to obtain situation awareness. Other aspects of situation awareness are influenced by operator- and equipment-related factors.

Situation Awareness: Operator Elements

Other aspects that affect situation awareness include an operator's

- Expertise
- Expectancies
- Workload and attention
- Automaticity
- Goals

Each can affect an operator's situation awareness and influence operator performance.

Expertise. As operators gain system experience they become increasingly expert at interpreting system cues and as a result, they need less time and fewer cues to obtain situation awareness. Researchers have argued that speed in recognizing the circumstances they are encountering distinguishes experts from novices. Previous system-related experience, as Orasanu (1993) notes, allows experienced operators to recognize or "see" the underlying structures of problems more quickly than can novices. Day and Goldstone (2012), for example, suggested that a critical element of experts' advantage over novices is in their speed of recognizing circumstances. Durso and Dattel (2006) described expertise as particularly useful in potentially hazardous situations, where experts are superior to novices in hazard perception and recognition. Memory also contributes to expertise as the better the operators' memory, the more experiences they can call upon to compare the current situation to ones they encountered previously.

Experts and novices also differ in response to dynamic situations. Federico (1995) compared expert and novice military personnel who examined identical simulated battlefield scenarios, and found that experts were considerably more context-dependent in evaluating situations than were novices, allowing them to evaluate situations more completely than novices. Experts were also found to multi-task better than novices. Cara and LaGrange (1999) determined that experienced nuclear power plant controllers anticipate events while they exercise system control, enabling them to quickly discern subtle system interactions. Endsley (2006) said that novice operators lack the knowledge to differentiate between information important to a particular situation and information that is not. "Without knowledge of the underlying relationships

among system components," she writes (p. 638), "novices do not realize what information to seek out following receipt of other information." Given these differences, in comparable circumstances experts can be expected to gain situation awareness more quickly and with fewer cues than can novices.

Training can compensate, in part, for inexperience by providing novice operators with system-related knowledge that experts have acquired (Tenney and Pew, 2006). Training can also allow operators to practice recognizing and responding to simulated unexpected or emergency system states, thus enabling them to respond appropriately should they encounter similar circumstances in actual operations.

Expectancies. Operators' mental models of system state guide them to the relevant situation cues, increasing the efficiency of their situation assessment. However, their mental models can also lead them to expect cues that may not be present in the actual environment. Jones (1997) and Jones and Endsley (2000), found that if operators' expectancies did not match the cues they encountered, whether because of their own incorrect mental models or because circumstances had changed after they had formed their mental models, they often failed to perceive cues critical to situation awareness, and hence they retained inaccurate situation awareness.

Unmet expectancies can also lead operators to misinterpret the cues they perceive, what Jones (1997) has termed "representational errors." Unfortunately, as Endsley (2000) notes, initial situation assessments are particularly resistant to change after operators have received conflicting information. An operator with deficient initial situation awareness may have difficulty obtaining more accurate situation awareness subsequently. Should the situation change subtly, the operator may not recognize situational changes.

Workload and Attention. Workload affects an operator's ability to attend to and interpret necessary cues, and thus it can directly affect situation awareness. In high workload conditions, which often occur in unexpected or nonroutine situations, operators might work so intensely to diagnose and understand the situation they are encountering that they have limited spare cognitive capacity to attend to multiple cues. In these circumstances they will attend to the most salient cues available, cues that may not necessarily be the most informative. On the other hand in low workload conditions operators may reduce their vigilance to the point that they attend to cues ineffectively, or fail to seek out the cues necessary for situation awareness.

Automaticity. Operators can compensate for the effects of high workload by using "automaticity" when completing tasks they had performed often. With repetition a task can become so familiar that it can be performed with little conscious effort. Many automobile operators, for example, who repeatedly drive the same route can become so adept at a task that they devote little attention to it, and attend to only limited situational cues (Logan, 1988), as if they are going through the motions without really thinking about what they are doing. However, in the event that they encounter new or unexpected cues, operators may pay a price for automaticity because they may fail to

notice changed cues and have difficulty modifying their situation awareness in response (Adams, Tenney, and Pew, 1995).

Goals. Goals help to guide operators to the information needed for situation awareness. A familiar aural alert, for example, guides operators to the information needed to comprehend the circumstances that led the alert. The alert acts as a goal, orienting operators to the information they need to obtain and maintain situation awareness.

Situation Awareness: Equipment Elements

In most systems operators depend largely on displays of visual information to recognize system state. Particularly if the system state changes in unexpected ways, operators need to quickly recognize what the system is doing, why it is doing that, and what the system state will be in the near term. Poorly presented displays can adversely affect an operator's ability to recognize and understand the cause of a change to system state. However, with sufficient experience, an operator may recognize the displays necessary to provide the critical information, something that inexperienced operators may be unable to do. Consequently, the impact of poorly presented information may not be equal across the board, but may affect experienced and inexperienced operators differently. Chapter 4 addressed many aspects of the presentation of system-related information and their effects on operator performance. The effects of two equipment features on operator situation awareness will be addressed presently, (1) cue salience and interpretability and (2) automation level.

Cue Salience and Interpretability. Displays that present information poorly require operators to expend more effort interpreting the data than do well-designed displays. Equipment designers have generally taken this into account when designing new systems. They have replaced analog displays that have one-to-one relationships to system components, in which displays and aural alerts can closely match operators' informational needs, with digital displays that have more flexibility in presenting critical information to operators in more interpretable ways than had analog displays. Advanced digital displays can also present information corresponding in salience to the urgency of the needed response, and, if necessary, guide operators to the desired responses.

In the discussion in Chapter 10 of the Boeing 737 that crashed in Washington, DC (National Transportation Safety Board, 1982), the pilots had approximately 30 seconds to understand what caused the engine instruments to display engine takeoff information in the manner presented, a presentation that the pilots had likely never encountered. This amount of time between takeoff and the decision point to safely continue or reject the takeoff was insufficient to enable them to interpret the data from the 10 engine-related gauges. The pilots primarily attended to two gauges that presented the most salient information, those that they had typically relied

upon within the group of 10 gauges. Unfortunately, those gauges presented inaccurate information. The other eight gauges presented the less salient, but accurate information.

The importance of cue salience is especially evident with respect to aural information. When multiple aural alerts are sounded, operators attend to the loudest or most prominent, especially when they are under stress or experiencing high workload. For this reason, designers generally have those alerts that are associated with the most critical system states the most prominent of the alerts.

Automation level. High levels of automation remove operators from direct involvement in system operations and alter the system-related information they receive, creating what has been referred to as "out of the loop performance" (Endsley and Kiris, 1995). Out-of-the-loop performance takes place when automated systems perform many of the system monitoring tasks operators had performed themselves, leaving them less attentive to the systems than they would otherwise have been, thus potentially reducing their situation awareness. This can be most critical during those operating phases when situation awareness is most needed. Because of the importance of automation to understanding operator error, this topic will be discussed more fully in Chapter 15.

Obtaining or Losing Situation Awareness

Obtaining Situation Awareness

Research has increased our knowledge of how operators obtain situation awareness. Mumaw, Roth, Vicente, and Burns (2000) observed nuclear power plant controllers and found that they gained situation awareness from a variety of sources, not exclusively from system displays and alerts, as had been thought. In addition to obtaining information from the displays, the operators actively sought out information from the operating environment. For example, as their shifts changed, departing operators briefed incoming ones about system-related events, and incoming operators probed the outgoing ones to obtain information. They also used control room logs and interacted with other operators, both from their own teams and those outside their immediate control room operating environments. Finally, because of the size of the control room in nuclear reactors was so large, operators would often walk through the facility to observe operations to obtain situation awareness.

Operators use a variety of techniques and strategies to obtain situation awareness. They rely extensively on displays for their information, they talk to other operators, they listen to changes in system-related sounds, and they also actively solicit and obtain information from other sources. As Mumaw et al. (2000) write,

> We emphasize the contribution of the various informal strategies and competencies that operators have developed to carry out monitoring effectively. Although these strategies are not part of the formal training programs or the official operating procedures, they are extremely important because they facilitate the complex demands of monitoring and compensate for poor interface design decisions. Thus one could effectively argue that the system works well, not despite but because of operators' deviations from formal practices. (p. 52)

Losing Situation Awareness

Limited operator exposure to a situation, inadequate training, poorly presented system information, and high workload, with other factors, can individually or in combination, adversely affect situation awareness. Other factors, such as automaticity, can also affect operator ability to deal with high workload situations, and limit their ability to perceive novel or unexpected cues.

Based on their training and experience with the system and on the available information that they obtain, operators develop mental models of system state, which serve as the basis for their situation awareness. However, they may lose situation awareness, or their mental models of the system states may no longer be accurate, for any number of reasons. Adams et al. (1995) studied the activities of airline pilots and found that pilots may fail to perceive cues that are subtly different from, but seemingly similar to, those associated with their mental models of the system state, especially if they are engaged in cognitively demanding tasks (see also Jones, 1997). Rather, as Jones and Endsley (2000) learned, operators were more likely to notice and alter their situation awareness when exposed to cues that were considerably different from those associated with their mental images. Therefore, the less cognitive effort operators expend in monitoring the system, the more likely they will fail to attend to critical situational cues.

Nevertheless, excessive cognitive effort may also lead to deficient situation awareness. Adams et al. (1995) suggest that when presented with ambiguous or incomplete information, operators may expend considerable cognitive effort to interpret the information. Their efforts can be so extensive as to distort, diminish, or even block their ability to perceive and comprehend arriving information.

Operators can also lose situation awareness when they are interrupted while performing a task that may require a number of steps to complete, as discussed in Chapter 10 with regard to the 1987 MD-80 accident in Detroit, Michigan. After the pilots had been interrupted during a critical checklist review they did not recognize that they had skipped an item in their checklist and consequently did not extend the flaps and slats before takeoff after (National Transportation Safety Board, 1988), thereby limiting the aircraft's aerodynamic capability that was necessary for takeoff. Yet, during periods of high workload operators will almost certainly face competing demands on their attention, and can often be interrupted during their activities. When

returning to their tasks their ability to maintain the situation awareness that they had acquired before the disruption will be reduced. As Adams et al. (1995) write with regard to airline pilots,

> To the extent that incoming information is unrelated to the task in which the pilot is concurrently engaged, its interpretation must involve considerable mental workload and risk. The more time and effort the pilot invests in its interpretation, the greater the potential for blocking reinstatement of the interrupted task as well as proper interpretation of other available data. The less time and effort invested in its interpretation, the greater the likelihood of misconstruing its implications. In a nutshell, choosing to focus attention on one set of events can be achieved only at the cost of diverting attention from all others. (p. 96)

In summary, high workload, competing task demands, and ambiguous cues can all contribute to an operator's loss of situation awareness, even with experienced and well-trained operators.

Decision Making

Accurate situation awareness is necessary for decision making. Operators with deficient or inaccurate situation awareness have difficulty interpreting system-related information and are likely to commit errors. Because of the influence of decision making on operator performance, and the critical role of decision errors in system safety, investigators should be familiar with the process and its role in error.

Operators generally apply one of two types of decision-making processes to the circumstances they encounter. One is appropriate to fairly static environments and the other to the dynamic environments of complex systems.

Classical Decision Making

In relatively static environments people usually employ "classical" decision-making processes, in which they,

1. Assess the situation
2. Identify the available options
3. Determine the costs and benefits (relative value) of each
4. Select the option with the lowest costs and highest benefit

Classical decision-making scenarios generally allow decision makers sufficient time to effectively assess the situation, identify and evaluate the various

options, and select the option with the greatest benefit and least perceived cost. Decision makers may value the benefits of a particular course of action to be greater than the value of an alternative one, the costs of an alternative path as greater than the costs of the selected path, or both (Strauch, 2016).

Decision makers generally complete these steps when there is sufficient time available, such as when making a major purchase, considering a job offer, selecting a candidate for a position, or even choosing the movie they will watch. For example, an automobile owner whose car has required multiple repairs, may, at some point, ask himself or herself whether to continue paying for repairs or buy a replacement vehicle instead. Evaluating the options, continue repairs or buy a replacement vehicle, depends on the owner's tolerance for unreliability, and for paying for the cost of replacement vehicle, as well as the cost of driving an older vehicle, as older ones typically require more maintenance than newer ones, and other factors that are specific to individuals. Ultimately, the owner's decision may well reflect nothing more than the availability of spare cash, but most people will make the decision on personal or family valuation of the costs and benefits of each alternative. The costs of making a bad decision in this and most classical decision-making scenarios are financial. Bad decisions cost the decision maker more money, either in the short- or long-term, than do good decisions.

Naturalistic Decision Making

In the often dynamic environments in which complex systems function, operators may not have sufficient time available to enable them to fully identify and value the available alternatives. Cues may be ambiguous, conflicting, and changing, options may not be fully identifiable, and the values of the operator may be irrelevant to what he or she thinks can best serve the system needs. As Klein (1993a) explains,

> Most systems must be operated under time pressure. Many systems must be operated with ill-defined goals…[and] shifting goals [that] refer to the fact that dynamic conditions may change what is important. Data problems are often inescapable. Decisions are made within the context of larger companies [that have their own priorities]. Tasks generally involve some amount of teamwork and coordination among different operators. Contextual factors such as acute stressors can come into play [such as] time pressure and uncertainty about data…Operators can't follow carefully defined procedures [and] finally, the decisions…involve high stakes, often [with] risk to lives and property. (pp. 16–19)

Rather than identify and then compare and select among alternatives, Klein (1993b) suggests that decision makers in dynamic situations employ what is referred to as recognition-primed decision making in which they recognize a situation based on their experiences and select the course of action appropriate to their perception of the situation.

Orasanu (1993) argues that naturalistic decision making, which takes place in the "naturalistic" environments of complex systems, is quantitatively and qualitatively different from the processes employed in classical situations. In dynamic situations naturalistic decision making is faster than classical decision making because decision makers bypass steps critical to effective decision making—identifying and evaluating alternatives. The process can be effective when applied to dynamic, rapidly changing circumstances. Further, unlike the static settings in which people employ classical decision making, in the dynamic settings in which complex system operations make decisions, circumstances may change rapidly, the circumstances may be ambiguous, and decision makers may encounter competing goals (Orasanu and Connolly, 1993). Moreover, unlike in classical decision-making scenarios, errors made in naturalistic settings can be personally risky to decision makers, posing consequences that are well beyond the potential financial costs of errors in classical decision-making milieus.

The naturalistic decision-making process may not necessarily lead to the "best" decision for the circumstances, but it will likely be good enough for the particular situation, a process also known as "satisficing" (e.g., Federico, 1995). As Orasanu (1993) notes, "A decision strategy that is 'good' enough, though not optimal, and is low in [the cognitive] cost [required to obtain the 'best' decision] may be more desirable than a very costly, and perhaps only marginally better, decision" (p. 151).

When the situation is highly dynamic, the decision maker experienced, and the available time brief, a naturalistic decision should lead to a more effective decision than one reached through the classical decision process. Because the decision will be reached quickly, it can be made with a reasonable likelihood of success, provided that the decision maker's initial assessment was accurate. However, should decision makers inaccurately assess the situation, naturalistic decision making can lead to poor decisions. In highly dynamic conditions, operators facing time pressure or stress will likely attend to the most salient cues and not necessarily the most informative ones. In the absence of a thorough situation assessment, operators can misperceive a situation and make ineffective decisions because the foundations of their decisions will have been flawed. As occurred in the 1982 Boeing 737 accident in Washington, DC (National Transportation Safety Board, 1982), the captain responded to cues—airspeed and engine thrust displays—that were inaccurate. His situation awareness was faulty and therefore his decision to take off was deficient, ultimately leading to the accident.

Heuristics and Biases

Biases in decision making refer not to dislikes of other people, but to decision-making processes that are "biased" in particular methods or outcomes. Such biases affect operator decision making in unexpected ways, often counter to what would be predicted exclusively by decision-making

models. Researchers suggest that biases influence decision making for very practical reasons. As Tversky and Kahneman (1974) suggest, in ambiguous situations "…people rely on a limited number of heuristic principles which reduce the complex tasks of assessing probabilities and predicting values to simpler judgmental operations" (p. 1124).

Wickens and Hollands (2000) describe a bias that many decision makers demonstrate after they have made a decision. As noted at the beginning of this chapter, people are often reluctant to alter decisions they have made, even in the face of evidence suggesting that their decisions and situation assessments were faulty. As in other domains, in a complex system reluctance to alter a decision in the face of contrary evidence can lead to error. Orasanu, Martin, and Davison (1998), following up on an National Transportation Safety Board study on pilot error accidents (National Transportation Safety Board, 1994), attribute many of the decision-making errors that they examined to "…errors in which the crew decided to continue with the original plan of action in the face of cues that suggested changing the course of action" (p. 5), which they called "plan continuation errors."

Wickens and Hollands (2000) suggest that decision makers tend to seek information that supports their initial hypothesis or decision, and avoid or discount information that supports a different decision or hypothesis (what they refer to as *disconfirmatory evidence*). As they write,

> Three possible reasons for this failure to seek disconfirmatory evidence may be proposed: (1) People have greater cognitive difficulty dealing with negative information than with positive information. (2) To change hypotheses–abandon an old one and reformulate a new one–requires a higher degree of cognitive effort than does the repeated acquisition of information consistent with an old hypothesis. Given a certain "cost of thinking" and the tendency of operators, particularly when under stress, to avoid troubleshooting strategies that impose a heavy workload on limited cognitive resources, operators tend to retain an old hypothesis rather than go to the trouble of formulating a new one. (3) In some instances, it may be possible for operators to influence the outcome of actions taken on the basis of the diagnosis, which will increase their belief that the diagnosis was correct. This is the idea of the "self-fulfilling prophecy." (p. 313)

An operator's reluctance or bias against altering decisions extends to a reluctance to accurately reassess the situation that led to the initial decision in the first place, and to an inability to accurately reevaluate the effects of that decision on the situation itself. Consequently, if an initial decision led to adverse consequences, the operator may well be reluctant to revisit the decision.

Errors Involving Naturalistic Decision Making

Klein (1999) argues that the concept of decision errors in real world settings may itself have little validity because of the often-untidy nature of those

settings. Orasanu, Martin, and Davision (2001), cite additional difficulties with the concept of errors in naturalistic decision making. As they note,

> Defining errors in naturalistic contexts is fraught with difficulties. Three stand out. First, errors typically are defined as deviations from a criterion of accuracy. However, the "best" decision in a natural work environment such as aviation may not be well defined, as it often is in highly structured laboratory tasks. Second, a loose coupling of decision processes and event outcomes works against using outcomes as reliable indicators of decision quality. Redundancies in the system can "save" a poor decision from serious consequences. Conversely, even the best decision may be overwhelmed by events over which the decision maker has no control, resulting in an undesirable outcome. A third problem is the danger of hindsight bias…a tendency to define errors by their consequences. These difficulties suggest that a viable definition of decision error must take into account both the nature of the decision process and the event outcome. (p. 210)

Yet, it is clear in reviewing accidents in complex systems that operators have made decisions that, even if appearing adequate at the time, are considered faulty after the fact.

This can be illustrated in a 1992 accident involving a Lockheed L-1011 that crashed after takeoff from John F. Kennedy International Airport in New York (National Transportation Safety Board, 1993). The pilots received a false aerodynamic stall warning just after the airplane lifted off the runway. They unsuccessfully attempted to return the airplane to the runway. By contrast, when other pilots had encountered the same false alert on that aircraft, at that point in the flight, they continued flying without incident, as called for in the airline's procedures. However, on this flight the first officer, who was the pilot handling the controls and flying the airplane, immediately said to the captain, "getting a stall" and then gave airplane control to the captain.

As noted previously, an aerodynamic stall is perhaps the most critical situation pilots could face; the airplane develops insufficient lift to remain flying and unless the situation is immediately corrected it will almost certainly crash. If this airplane was indeed about to stall, as the first officer had told the captain, continuing the flight would have meant almost certain catastrophe. Given the airplane's close proximity to the ground there was little or no possibility that the captain could have taken the necessary actions to avoid a stall. However, because of the airplane's high speed and heavy takeoff weight, with the limited runway distance remaining, attempting to land the airplane also meant an almost certain accident.

The captain's decision to land clearly led to the accident. However, because the first officer had erroneously interpreted the stall warning and told the captain that the airplane was about to stall, in the limited time available the captain's ability to effectively assess the situation, difficult at best, was

almost impossible to achieve. As a result, he gave more weight to the first officer's pronouncement than he would likely have given otherwise. The captain's inaccurate situation awareness about an impending stall, albeit an awareness largely influenced by the erroneous assessment of another team member, led to the decision to attempt to land.

The Effects of Operators in Similar Circumstances. Rhoda and Pawlak (1999) studied commercial flights into one airport, Dallas-Ft. Worth International Airport, during thunderstorms. Interestingly, they found that pilots were more likely to fly into thunderstorms, weather that creates substantial risk to flight safety, when similar aircraft were preceding them than when not. Operators flying similar aircraft were considerably influenced by the decisions and actions of those who, in the time preceding their exposure to similar circumstances, made decisions that they may not necessarily have made when not following those aircraft. Operators in those situations may be thinking that those ahead successfully dealt with the risk and therefore, the risk to them is (1) manageable and (2) not as great as possibly thought.

Decision-Making Quality versus Decision Quality

The difficulty of examining decision-making errors in systems can be attributed, in part, to difficulties of distinguishing between the quality of the decision-making process and the quality of the decision itself. The two are similar, but the quality of a decision should not be used to gauge the quality of the process used to reach that decision. Applying good decision-making techniques, such as systematically obtaining, soliciting, and comprehending available system information, does not guarantee that decisions will be effective; poor decisions can follow good decision making.

For example, investigators may conclude that an operator properly interpreted the available information, effectively solicited information about the system and its operating environment, and still made a decision that later proved to be ineffective or worse, led to an accident. In addition, circumstances in complex systems may be so dynamic that the critical information changed after an operator initially obtained situation awareness. Although a systematic process is required for a "good" decision, decisions will only be as good as the information upon which they are based, and upon the circumstances being encountered.

Case Study

On June 14, 2003, the charter fishing vessel *Taki-Tooo*, capsized in the Pacific Ocean, after its captain crossed the bar at the Tillamook Bay inlet en route to the ocean, for an intended day-long fishing trip. The 32-foot vessel had been

charted by a group of friends who had traveled several hundred miles specifically for the trip, and who had gone together on previous trips with the captain. They had specifically asked for this captain to serve as vessel master on this trip. Of the 17 passengers and 2 crew onboard, the captain and 10 of the passengers were killed in the accident (National Transportation Safety Board, 2005).

The group assembled at the marina early morning, departing on the vessel about 06:05 local time. The captain transited the inlet to the bar, which separated the inlet from the Pacific Ocean, and waited there for favorable seas; the sea state at the bar was particularly rough that morning. Investigators attempted to answer the question, why did the captain attempt to cross the bar knowing that the risk of an erroneous decision could be catastrophic to him and his passengers?

Although recorded communications and electronic data were not available, other data allowed investigators to reliably reconstruct the scenario. These data included reports from *Taki-Tooo* survivors and from those on the vessels that had crossed the bar before the *Taki-Tooo* captain attempted to do so, weather data, computer records of the captain's accessing weather data, Coast Guard observations, the captain's previous experience in the area, and in particular, reports of vessel captains who crossed the bar that morning, their vessel sizes, and the timing of their crossings. Together investigators were able to not only reconstruct the accident circumstances but to describe the captain's decision making as well.

Investigators determined that the captain was aware of the sea conditions that morning. The night before he had accessed weather information about the bar from his home computer. On the morning drives from his home to the marina, when serving as captain, he was reported to have listened to local marine weather broadcasts. Further, the U.S. Coast Guard, which maintained an observation base there, warned mariners when sea conditions at that bar were particularly challenging and they had so warned mariners that morning. The U.S. National Weather Service had forecast and then issued small craft advisories for the area, advisories that were disseminated when winds and sea conditions were between 20 and 33 knots and seas greater than 7 feet.

After leaving the marina he arrived at the bar about 30 minutes later, where he waited until 07:15. Three other vessels waited with the *Taki-Tooo*, each of which successfully crossed the bar and reached the ocean. At 07:15 this captain attempted to do the same, but the vessel was struck by a wave and capsized.

Information Available

Investigators focused on the background of the captain, and the circumstances under which he made the decision to cross, to understand the nature of his decision-making error in deciding to cross. The captain was 66-years

old and had over 26 years of experience operating charter fishing vessels, primarily in the Tillamook Bay area. He and his wife had owned the company that owned and operated the *Taki-Tooo* and another vessel, but had sold it about 2 years before the accident. The captain agreed to serve thereafter on a part-time basis as captain of the *Taki-Tooo* upon the request of the group chartering the vessel. He was to be paid upon completion of the charter, but investigators determined that he did not make the decision to cross for financial need. He and his wife were said to have sold the company as part of their retirement planning.

Thus, the captain, a mariner with years of experience operating charter fishing vessels in this area, was skilled, understood weather information, and was, because of his experience, cognizant of the hazards the sea state presented. In situation awareness terms, he had Levels 1 and 2 situation awareness. He had all of the information necessary regarding the sea state, Level 1, and he understood the meaning of the weather information in terms of the risks it posed to his vessel, Level 2.

But investigators determined that several factors influenced his decision. First, although his passengers would have understood had the captain decided not to cross for safety reasons, he knew the passengers and was aware that they had asked for him to serve as captain. This knowledge would have made him less willing to disappoint them. As investigators write:

> …the knowledge that the passenger group chartering his vessel had specifically requested that he serve as their master would most likely have subtly affected his decision not only to leave port but also to subsequently cross the bar. He would have been motivated not to disappoint those passengers who had traveled some distance to engage in a fishing expedition under his command. (National Transportation Safety Board, 2005, pp. 43–44)

Further, by traveling to the bar and waiting, with the other vessels, for a sea state that would have allowed a safe crossing, he, with the other vessel captains, also limited his options with the passengers. Investigators write, with regard to the decisions of those vessel masters:

> While the decision to leave the dock to assess conditions at the bar might have been prudent, it also probably subtly influenced the masters' subsequent decisions to cross the bar rather than return to the dock. By loading passengers on the vessel and taking them almost as far as the bar, the masters' decision-making ability to return to the dock without crossing the bar was diminished. To return to the dock would have meant that each master would have had to personally face and explain his decision to the passengers who had prepared for the expedition and boarded the vessel and whose anticipation for the fishing voyage no doubt had

> increased as they neared the bar. (National Transportation Safety Board, 2005, p. 43)

In addition, the years of experience of the captain operating charter fishing vessels in that area may have worked against the quality of his decision making. His previous efforts crossing the bar had all been successful. As a result, even given his awareness of the risks of crossing, experiencing only successful crossings may have influenced his perception of the risk. As Orasanu and Martin (1998, p. 103) observed with regard to aviation,

> If somewhat similar risky situations have been encountered in the past and the crew has successfully taken a particular course of action, they will expect also to succeed this time with the same CoA [course of action], for example, landing at airports where conditions frequently are bad, for example in Alaska. Given the uncertainty of outcomes, in many cases they will be correct, but not always.

As noted, after the *Taki-Tooo* arrived at the bar and waited with three other vessels, the captains of those vessels crossed successfully. Vessel size and engine power affect vessel stability. The larger the vessel and the more powerful its engine, the more readily it can withstand rough seas. The first two vessels that crossed were larger than the *Taki-Tooo* and had more powerful engines. The one that crossed immediately before the captain attempted to do so was about the same size, and with the same approximate sized engine as the *Taki-Tooo*. Because the captain and his wife had owned that vessel through the company that they had sold, and having operated it before, the captain was familiar with its stability and handling characteristics. Once that vessel crossed the captain had evidence that a comparably sized vessel could successfully cross the bar.

Nonetheless, despite the successful outcomes of the vessels that crossed before the *Taki-Tooo* captain's attempt, those crossings were not uneventful. Some onboard one of the vessels reported having sustained injuries during the crossing. Most important, however, to the captain's decision was the nature of the dynamic conditions the sea presented and the length of the interval between deciding to cross and actually crossing the bar. Because the crossing could not be instantaneous, any decision to cross could not have been based on the sea state encountered during the crossing, given the dynamic sea conditions and the time needed to reach the bar from the point at which the decision to cross had been made. In terms of situation awareness, no captain at the bar could have had Level 3 situation awareness. The time interval between the decision and the encounter, and the severity of the sea state meant that situation awareness would be inaccurate, and any decision based on inaccurate situation awareness has a likelihood of being erroneous. Investigators conclude:

> … the decision of the *Taki-Tooo* master to cross the bar was probably influenced by a host of factors, including the request of the passengers for his services, his observations of sea conditions comparable to those he had seen before, his previous experience making the bar transit with this vessel, and his observation of the crossings of the other vessels before him. [However], no master can be assured that conditions encountered when crossing will be the same conditions as those observed when the decision to cross is made. The tragic consequences of his attempt to transit the bar demonstrate the faultiness of his decision-making. (National Transportation Safety Board, 2005, p. 46)

Summary

Operators conduct a situation assessment to understand the system state and its operating environment. Situation awareness is the understanding operators have of the system and its environment at any one time. It is based on an operator's obtaining critical system-related information, understanding the information and its description of the system state, and being able to project from the current system state to the near term. Equipment factors, such as display interpretability; operator factors, such as experience, knowledge, and skills; and company factors, such as training, affect situation awareness quality. The quality of situation awareness directly affects the quality of subsequent decision making.

In general, operators use one of two types of decision-making processes. One, classical decision making, is applied primarily to relatively static situations and the other, naturalistic decision making, is applied primarily to dynamic situations. In classical decision making the decision maker generates options based on the nature of the situation, evaluates the costs and benefits of the options, and selects the one with the greatest benefits for the least cost. In naturalistic decision making, the decision maker quickly makes a decision by first recognizing the situation and then selecting an option that seems to work for that situation, even if it is not necessarily the "best" option that could follow a more thorough analysis. Decision-making biases influence the quality of decisions made through either process.

DOCUMENTING SITUATION AWARENESS AND DECISION MAKING

SITUATION AWARENESS

- Identify the information that the operator used or, if the operator is unavailable, was likely to have used to obtain situation awareness.

- Document equipment, operator, and company antecedents that could have affected the operator's understanding of the event.
- Document the system state from recorded data, operating manuals, personnel interviews, and other relevant data sources.
- Observe system operations, if possible, to determine the information upon which the operators relied.
- Interview operators, both critical and noncritical to the event, to learn of the techniques they use to understand the state of the system and its operating environment.
- Document the sources of information available to the operator, using the methods described in the preceding chapters.
- Identify the operator's previous encounters with similar scenarios in similar systems.
- Document the time the operator first perceived the critical situation and the time he or she responded.
- Compare the operator's perceptions of the events with the actual system state.

DECISION MAKING

- Document the tasks that the operator performed, and the amount of time available to complete the tasks.
- Determine the information available, and the information that the operator used.
- Identify the operator's decisions and actions.
- Evaluate the effectiveness of the decisions in terms of their consequences as well as the decision-making process used.
- Examine training programs and procedures to identify deficiencies that could have led to adverse outcomes.
- Examine the circumstances the operator encountered and the extent to which they changed between the time a decision was made and the time it was implemented.

References

Adams, M. J., Tenney, Y. J., and Pew, R. W. 1995. Situation awareness and the cognitive measurement of complex systems. *Human Factors*, 37, 85–104.

Byrne, E. 2015. Commentary on Endsley's "situation awareness misconceptions and misunderstandings." *Journal of Cognitive Engineering and Decision Making*, 9, 84–86.

Cara, F. and LaGrange, V. 1999. Emerging expertise in process control. *Ergonomics*, 42, 1418–1430.

Clark, C. 2012. *The sleepwalkers: How Europe went to war in 1914*. New York, NY: HarperCollins.

Day, S. B. and Goldstone, R. L. 2012. The import of knowledge export: Connecting findings and theories of transfer of learning. *Educational Psychologist*, 47, 153–176.

Durso, F. T. and Dattel, A. R. 2006. Expertise and transportation. In K. A. Ericsson, N. Charness, P. J. Feltovich, and R. R. Hoffman (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 355–372). Cambridge, UK: Cambridge University Press.

Endsley, M. R. 1995. Toward a theory of situation awareness. *Human Factors*, 37, 32–64.

Endsley, M. R. 2000. Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley and D. J. Garland (Eds.), *Situation awareness: Analysis and measurement* (pp. 3–32). Mahwah, NJ: Erlbaum.

Endsley, M. R. 2006. Expertise and situation awareness. In K. A. Ericsson, N. Charness, P. J. Feltovich, and R. R. Hoffman (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 633–652). Cambridge, UK: Cambridge University Press.

Endsley, M. R. 2015. Situation awareness misconceptions and misunderstandings. *Journal of Cognitive Engineering and Decision Making*, 9, 4–32.

Endsley, M. R. and Kiris, E. O. 1995. The out-of-the-loop performance problem and level of control in automation. *Human Factors*, 37, 381–394.

Federico, P. A. 1995. Expert and novice recognition of similar situations. *Human Factors*, 37, 105–122.

Jones, D. G. 1997. Reducing situation awareness errors in air traffic control. *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Jones, D. G. and Endsley, M. R. 2000. Overcoming representational errors in complex environments. *Human Factors*, 42, 367–378.

Klein, G. 1993a. A recognition-primed decision (RPD) model of rapid decision making. In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 138–147). Norwood, NJ: Ablex.

Klein, G. 1993b *Naturalistic decision making: Implications for design*. Wright-Patterson Air Force Base, OH: Crew System Ergonomics Information Center. Logan, G. D. 1988.

Klein, G. 1999. Applied decision making. In P. A. Hancock, (Ed.), *Human performance and ergonomics* (pp. 87–107). San Diego, CA: Academic Press.

Logan, G. D. 1988. Automaticity, resources, and memory: Theoretical controversies and practical implications. *Human Factors*, 30, 583–598.

Mumaw, R. J., Roth, E. M., Vicente, K. J., and Burns, C. M. 2000. There is more to monitoring a nuclear power plant than meets the eye. *Human Factors*, 42, 36–55.

National Transportation Safety Board. 1982. Aircraft accident report, Air Florida, Inc., Boeing 737-222, N62AF, Collision with 14th Street Bridge, near Washington National Airport, Washington, DC, January 13, 1982. Report Number: AAR-82-08. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1988. Aircraft accident report, Northwest Airlines, Inc., McDonnell Douglas DC-9-82, N312RC, Detroit Metropolitan Wayne County Airport, Romulus, Michigan, August 16, 1987. Report Number: AAR-88-05. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1993. Aircraft accident report, aborted takeoff shortly after liftoff, Trans World Airlines flight 843, Lockheed L-1011, N11002, John F. Kennedy International Airport Jamaica, New York July 30, 1992. Report Number: AAR-93-04. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1994. *Special study, a review of flightcrew-involved, major accidents of U.S. air carriers, 1978 through 1990.* Report Number: SS-94-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2005. Marine accident report, capsizing of U. S. small passenger vessel, Taki-Tooo, Tillamook Bay Inlet, Oregon, June 14, 2003. Report Number MAR-05/02. Washington, DC: National Transportation Safety Board.

Orasanu, J. and Connolly, T. 1993. The reinvention of decision making. In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 3–20). Norwood, NJ: Ablex.

Orasanu, J. and Martin, L. 1998. Errors in aviation decision making: A factor in accidents and incidents. Paper presented at HESSD 98. *Working Conference on Human Error, Safety and Systems Development* (pp. 100–107). Seattle, WA.

Orasanu, J. M. 1993. Decision-making in the cockpit. In E. L. Wiener, B. G. Kanki, and R. L. Helmreich (Eds.), *Cockpit resource management* (pp. 137–172). New York, NY: Academic Press.

Orasanu, J. M., Martin, L., and Davison, J. 1998. Errors in aviation decision making: Bad decisions or bad luck. *Paper Presented at the Fourth Conference on Naturalistic Decision Making*, Warrenton, VA, May 29–31.

Orasanu, J. M., Martin, L., and Davison, J. 2001. Cognitive and contextual factors in aviation accidents: Decision errors. In E. Salas and G. Klein (Eds.), *Linking expertise and naturalistic decision making* (pp. 209–225). Mahwah, NJ: Erlbaum.

Rhoda, D. A. and Pawlak, M. L. 1999. *An assessment of thunderstorm penetrations and deviations by commercial aircraft in the terminal area*. Project Report NASA/A-2. Lexington, MA: MIT Lincoln Laboratory.

Strauch, B. 2016. Decision errors and accidents: Applying naturalistic decision making to accident investigations. *Journal of Cognitive Engineering and Decision Making*, 10, 281–290.

Tenney, Y. J. and Pew, R. W. 2006. Situation awareness catches on: What? So what? Now what? *Reviews of Human Factors and Ergonomics*, 2, 1–34.

Tuchman, B. 1962. *The guns of August*. New York, NY: Macmillan.

Tversky, A. and Kahneman, D. 1974. Judgment under uncertainty: Heuristics and biases. *Science*, 185, 1124–1131.

van Winsen, R. and Dekker, S. W. A. 2015. SA anno 1995: A commitment to the 17th century. *Journal of Cognitive Engineering and Decision Making*, 9, 51–54.

Wickens, C. D. and Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.

15

Automation

"David, I'm afraid."
Hal the computer to astronaut David Poole as he was removing Hal's higher cognitive powers, in Stanley Kubrick's film, *2001: A Space Odyssey**

Introduction

Although much of the technological innovations that Stanley Kubrick had envisioned in his landmark 1968 film, *2001: A Space Odyssey*, have not been realized, dramatic changes have nonetheless taken place in complex systems since then. Unlike Hal, the omniscient and omnipotent computer, automation today does not exercise absolute control over complex systems and the people who operate them. Operators still control complex systems, although their role has changed as automation has increased and grown more sophisticated.

As systems have become more advanced, automation has performed an ever-larger share of both the manual and the cognitive tasks that operators had previously done themselves. The increased role of automation in systems has enhanced many aspects of system operations, but it has also led to unique antecedents to errors, errors that have led to incidents and accidents.

Two aircraft incidents, involving what today would be considered relatively simple automation, illustrate the type of operator errors that could result from the application of automation to complex systems. In each, the aircraft sustained substantial damage but the pilots were able to land safely. In 1979, a DC-10 experienced an aerodynamic stall and lost over 10,000 feet of altitude before the pilots recovered airplane control. They had inadvertently commanded a control mode through the airplane's autopilot that called for a constant speed climb, but during the climb they did not realize that the airspeed had decreased below the stall speed (National Transportation Safety Board, 1980).

* The quote, taken from the film, was not in the Arthur C. Clarke novel upon which the film was based.

As discussed previously in this text, an aircraft experiencing an aerodynamic stall develops insufficient lift to maintain flight. Unless pilots respond quickly the aircraft will almost certainly lose altitude rapidly and crash. In this accident the pilots had engaged an automated flight mode that maintained the pilot selected climb rate. However, with no other changes to aircraft control, a climbing aircraft can only maintain a constant climb rate at the expense of its forward airspeed. At some point, the airspeed will be insufficient to develop lift and the airplane will stall.

The pilots had delegated airplane control to the autopilot, but did not effectively monitor the aircraft's performance thereafter. Instead, they relied on it to perform accurately and reliably, but did not notice that the airplane's airspeed had decreased below the minimum required to maintain forward air speed and lift. Despite three sources of data presented visually, aurally, and tactilely informing them of their insufficient airspeed and the stall, none recognized that the airplane had experienced a stall.

Several years later a Boeing 747 lost power on an outboard engine while in cruise flight (National Transportation Safety Board, 1986). Should an engine on an aircraft with four engines fail, the two engines on the other wing would generate about twice the thrust as the remaining engine alone could generate. Without corrective action, the differential thrust would cause the airplane to swing or "yaw" to the side of the failed engine.

An engine failure is not a catastrophic event, so long as the pilots perform maneuvers that all pilots are trained to perform to maintain aircraft control. However, these pilots did not respond to the engine failure and did not perform the necessary actions to correct the yaw. The autopilot continued to counteract the yaw in order to maintain the selected flight path. However, after several minutes, the autopilot could no longer maintain the heading and it automatically disengaged from airplane control. The airplane entered a steep dive and lost over 30,000 feet before it was recovered. The pilots neither recognized nor responded effectively to the situation until the airplane had reached the end of the dive.

In both instances, what today would be considered relatively primitive types of aircraft automation performed precisely as designed. The DC-10 pilots failed to monitor the actions of the automation mode that they had selected, and the Boeing 747 pilots did not disengage the automation and take manual control of the airplane when necessary. Neither of the two pilot teams seemed to recognize that the automation, which had performed so reliably in the past, could also lead to catastrophe if not monitored.

Since then the application of automation to complex systems has increased, and more sophisticated types of automation applied, but operators have continued to make errors interacting with the automation. For example, a highly automated aircraft that was introduced in the late 1980s and operated by different airlines, each with its own operating procedures, was initially involved in a number of fatal accidents due, at least in part, to operator errors in dealing with the automation. The relatively high number of accidents of

this airplane type illustrates a phenomenon that seems to occur after technologically advanced systems have begun service, a lengthy initial period in which managers and regulators come to recognize how the new technology requires changes in the way operators deal with the system. Training programs and procedures are then modified in response to the effects of the technological advances. As Amalberti writes (1998),

> Any new technology calls for a period of adaptation to eliminate residual problems and to allow users to adapt to it. The major reason for this long adaptive process is the need for harmonization between the new design on one hand and the policies, procedures, and moreover the mentalities of the…system on the other hand. (p. 173)

To better understand how automation can affect operator performance, the nature of automation itself will be examined, and effects of automation on system operations reviewed.

Automation

Automation can mean many things to many people. Billings (1997) defines automation as the replacement of tasks that humans had previously performed by machines. Moray, Inagaki, and Itoh (2000) define automation as "any sensing, detection, information-processing, decision making, or control action that could be performed by humans but is actually performed by machine" (p. 44).

Automated systems can perform a wide range of both manual and cognitive tasks, ranging from minimal to complete system control. Indeed, when planning complex systems, designers decide on the level of automation to bring to the system. Parasuraman (2000) and Parasuraman et al. (2000) describe up to 10 levels of automated control that designers can incorporate into a system, from a fully manual system to complete automated system control. In the lowest level, the operator performs all tasks, and in the highest level the automation makes all decisions and takes all actions independent of, and without communicating with, the operator. The levels in between range from automated sensing and detection, to offering operators decision alternatives, to deciding for the operator, to the highest level, complete control. They recommend that designers consider the level of automation that is optimum for the operator tasks they wish to automate, and the effects of the automation level on the operator's ability to perform the requisite tasks.

Others argue that the severity and immediacy of error consequences should dictate the level of automation implemented. Moray et al. (2000) believe that the optimal level of automation depends on such elements as the

complexity of the system, the risk of a fault, and the dynamics of an event. They suggest that an immediate response to a system fault is needed when an automated response will be superior to a human one. However, to avoid unnecessary and quite costly system shutdowns in situations that are not time critical, they suggest that operators, not the automation, retain ultimate control of the system.

Today the variety of automated systems employed and their levels of automated control are considerable. Automation can function as a single subsystem or as a constellation of subsystems operating interdependently. Nevertheless, despite the range of possible automation functions available, automated systems currently perform four functions: acquiring information, analyzing information, selecting actions based on that analysis, and implementing the action, as needed (Sheridan and Parasuraman, 2005). The degree and level at which the four functions are conducted vary across systems, along with their degree of independence from the operators. Today, after extensive research into automation's effects on operator performance has been carried out and several automation-related events have occurred, many recognize that automation has led to many positive and negative effects on operator performance.

Automation Advantages and Disadvantages

Benefits

There is little question that automation has enhanced many aspects of complex system operations. Wiener and Curry (1980) and Wiener (1989) examining the effects of automation in the aviation environment, believe that these resulted from a combination of technological, economic, and safety factors, not all of which have been realized. For example, automation can reduce operator workload, enabling operators to attend to "higher level" activities, such as system monitoring and troubleshooting. Automation can also raise operator productivity decreasing the number of operators needed and lowering operating costs. Automated systems are also highly reliable and can control system performance with considerable accuracy. In aviation and marine settings, for example, automated navigation systems can maintain operator-selected courses or tracks with little or no deviation, and with little or no operator involvement necessary to ensure the accuracy of the maintained course.

Modern systems also offer flexibility to the design of both displays and controls. This enhances safety by enabling designers to display potentially readily interpretable and accurate system-related information, benefitting situation awareness and increasing operators' abilities to recognize and respond effectively to system anomalies. Digital displays can integrate and

present data with fewer gauges, and in a more interpretable manner than could be done with analog gauges, and controls can be designed to better match the needs of operators than in older, nonautomated systems.

Shortcomings

Automation has also brought about negative consequences that, on occasion, have adversely affected operator performance and increased opportunities for error. In some ways, the benefits of automation, such as its high reliability and accurate system control can be seen to actually work against operator performance. As Jamieson and Vicente (2005) note:

> The use of automation in complex sociotechnical systems has proved to be a double-edged sword. It is a technology that, perhaps more so than any other, speaks with a forked tongue to system designers. On the one hand, it promises unprecedented reliability, reduced workload, improved economy, and fewer errors. On the other hand, it whispers of less tangible, but no less real, costs to operators in terms of skill degradation, mental isolation, and monitoring burdens…(p. 12)

Researchers have identified several effects of automation that can potentially work against operator performance, and thus create opportunities for errors.

User Interface. Some automation applications have reduced the types and amount of data that operators had depended upon for system performance feedback, thereby reducing operator's awareness of the system state (e.g., Norman, 1990; Billings, 1997). Feedback reduction can be seen in several highly automated aircraft types. Two interconnected pilot control columns that pilots had used to control the flight path also enabled each to observe the other's control column movements through corresponding movement in their own controls. These have been replaced by control sticks with no corresponding movement. Moving one does not move the other. Pilots using these controls cannot rely on tactile and visual feedback from control column movement to recognize the other pilot's inputs as they could on older models. Rather, they must focus on flight displays and interpret the data to recognize the results of changes to aircraft controls.

Similarly, in older aircraft pilots move throttles or control levers forward or back to increase or decrease engine thrust. On aircraft equipped with autothrottles, engine thrust is automatically maintained, varying in response to pilot selected performance parameters, environmental conditions, design limitations, and operating phase. On most autothrottle-equipped aircraft, pilots have two sources of information to inform them of autothrottle commanded changes in engine thrust: forward and aft throttle movement and engine-related data displays. However, on some advanced aircraft stationary throttles have replaced moving throttles, thus eliminating visual and tactile cues of throttle movement that pilots had

relied upon to detect engine thrust changes. This has reduced the available sources of information on engine thrust changes to one source, visually presented information from engine displays. Worse, with changes to both controls pilots have been forced to rely on their foveal or central vision to learn of changes in engine operation, rather than their peripheral vision. Because peripheral vision is more sensitive to changes in movement than central vision, control changes have become even less detectable than they had been before.

Automation has also changed the design of system controls by making extensive use of keyboards, touchscreens, trackballs, and other control types, rather than the larger and more defined levers, pulleys, and manual controls found on older systems. In routine situations in which operator workload is predictable, controlling the system through keyboard or touchscreen will likely not affect operator performance. However, in nonroutine situations, when operator workload is likely to be high, interacting with the automated controls can be cognitively demanding, reducing operator awareness of peripheral visual cues and increasing workload further in inopportune circumstances.

For example, in automated systems activities can be programmed through a small keyboard, potentially reducing workload because further control inputs would not necessarily be needed—so long as the programmed activities do not change. However, should they need to change, operators will have to execute numerous keystrokes again, during periods of high workload. Attending to the keyboard and inputting keystrokes increase workload substantially over the steps that would be required in less-automated systems and during unexpected or nonroutine situations, and the increase on operator workload can have adverse effects on operational safety.

System Transparency. Few operators are aware of the design or logic of the software and the contents of the algorithms and databases that guide the automation of the systems they operate. As many software users do, rather than understanding a program's underlying design, operators strive to become sufficiently familiar with its application, either through formal training, experience, or both, to operate it as needed. In most circumstances, the lack of automation logic transparency, what Woods, Johannesen, Cook, and Sarter (1994), describe as the "opaque" nature of automation, will not adversely affect operator performance. However, in the event of a system anomaly, operators' unawareness of the reasons for the actions of the automation, or the inability to predict its next actions, degrades their ability to diagnose and respond. As Billings (1997) notes, "regardless of the cause, the net effect [of this] is diminished awareness of the situation, a serious problem in a dynamic environment" (p. 188).

Further, automation opacity makes operators reluctant to intervene should they become uncertain of the automation outcomes to expect. Sarter and Woods (2000) found that when airline pilots were faced with unexpected

automation actions, they hesitated to become more involved in the system's operation. Instead, most persisted in attempting to understand the nature of the error, even to the point of not monitoring the airplane's operation and allowing it to enter potentially dangerous conditions.

In some systems the automation is sufficiently independent that it can engage one of multiple operating modes without operator input or guidance. Each operating mode offers capabilities specific to the needs of the various operating phases, but the system may not effectively inform operators of the identity of the mode that is engaged. Several researchers have found that operators were often unaware of the system's operating mode, a potentially critical element of situation awareness in any complex system (e.g., Sarter and Woods, 1995, 1997, 2000; Degani, Shafto, and Kirlik, 1999).

Sarter and Woods (1997) characterize mode changes and related phenomena that operators do not expect as "automation surprises," which, "begin with misassessments and miscommunications between the automation and the operator(s), which lead to a gap between the operator's understanding of what the automated systems are set up to do and how the automated systems are or will be handling the underlying process(es)" (p. 554). They suggest that automation surprises are based on poor operator mental models of automation, as well as low system observability during highly dynamic or nonroutine situations. By itself the loss of mode awareness, that is, situation awareness with regard to system operating mode, can create opportunities for error. However, in combination with automation opacity, loss of mode awareness can considerably reduce operator situation awareness and enhance opportunities for error.

The effects of several of these automation effects are evident in the December 1995 accident involving a Boeing 757 that crashed near Cali, Colombia (Aeronautica Civil of the Government of Colombia, 1996). The crew was using the airplane's automated flight management system to control the flight. The captain misinterpreted an air traffic controller's clearance to Cali and reprogrammed the aircraft automation to fly directly to the Cali radio navigation beacon rather than to waypoints located short of the field, as the approach procedure had required. When told to report passing over a waypoint in between, both pilots were unaware that the captain had inadvertently deleted the critical waypoint and all intermediate waypoints from the automated flight path control by establishing the direct course to the Cali beacon.

After repeated, unsuccessful attempts to locate the critical waypoint through the automation, they decided to fly to a waypoint just short of the field, again by reprogramming the automation to fly the new flight path, during an already period of high workload. However, they were unfamiliar with the designation of navigation data stored in the airplane's navigation database, and inadvertently established a course away from Cali. After the crew had recognized their error and they turned back to Cali, the airplane struck a mountain.

Monitoring, Vigilance, and Situation Awareness. Automation has helped to distance the operator from many system-related cues. Norman (1981, 1988) believes that in automated systems operators may no longer directly observe the system, hear its sounds, or feel its movement. Instead they monitor the data that automated sensors detect and display; which may not effectively convey the needed information. This diminished their mode awareness and decreased their ability to respond effectively to unexpected system states. Further, monitoring displays over extended periods is fatiguing. Operators lose the ability to accurately detect and respond to system anomalies after prolonged periods of monitoring (e.g., Wiener and Curry, 1980; Molloy and Parasuraman, 1996; Parasuraman, Mouloua, Molloy, and Hillburn, 1996).

Researchers have demonstrated that increasing automation and decreasing operator involvement in system control reduces operator ability to maintain awareness of the system and its operating states. Endsley and Kaber (1999) found that among various levels of automation, people perform best when actively involved in system operation. Endsley and Kiris (1995) term the reduced operator involvement in system control in highly automated systems the "out-of-the-loop performance problem." They argue that automation leads to reduced operator ability to recognize system anomalies as a result of (1) reduced vigilance and increased complacency from monitoring instead of active system control, (2) passive receipt of information rather than active information acquisition, and (3) loss or modification of feedback concerning system state.

The investigation of a 1997 accident involving an automated turboprop aircraft, an Embraer Brasilia, support these conclusions (National Transportation Safety Board, 1998). The pilots did not recognize that the wings of their aircraft had become contaminated by ice, degrading its aerodynamic characteristics. The autopilot, a sophisticated flight management system, attempted to maintain the selected flight path of the increasingly unstable aircraft.

Because the pilots were not directly controlling the airplane they had no tactile feedback from the movement of the control column. Only two sources of visual information were available to inform them of the airplane's increasing loss of lift, an airplane attitude display and the autopilot-induced control column movements, which corresponded to what would have been pilot-induced control column movements. The pilots did not perceive these cues and so did not recognize that the airplane was about to stall.

The autopilot reached the limit of its control ability and disengaged. The airplane quickly went into a turn and then dive, and the pilots were unable to regain aircraft control. Had they been controlling the airplane manually, the tactile cues of the control column forces would have been far more perceptible than were the visual cues of the displays because they would have felt the control column forces or seen them through their peripheral vision, unlike the visual displays that required direct monitoring. With the

movement of the control column the pilots would have recognized that the airplane was approaching a stall. With that information they would have likely responded in sufficient time to avoid the accident.

Workload Alteration. Automation has generally reduced operator workload; but it has often done so during already low-workload operating phases, and it has increased it during already high-workload phases. Woods (1996) has described this redistribution of workload as "clumsy automation" (also Kantowitz and Campbell, 1996), a phenomenon that increases rather than decreases opportunities for operator errors. As Woods (1996) explains,

> A form of poor coordination between the human and machine in the control of dynamic processes where the benefits of the new technology accrue during workload troughs and the costs or burdens imposed by the technology (i.e., additional tasks, new knowledge, forcing the user to adopt new cognitive strategies, new communication burdens, new attentional demands) occur during periods of peak workload, high criticality or high tempo operations… (p. 10)

Yet even simply reducing workload can also degrade operator performance if this occurs during already low workload periods. Excessively reduced workload over extended periods can increase boredom and increase operator difficulty in maintaining vigilance (O'Hanlon, 1981). As noted in Chapter 6, operator alertness decreases over extended periods of relative inactivity, increasing the subsequent effort needed to detect system anomalies.

Trust, Bias, and Skill Degradation. Automation can perform so reliably and accurately that over time operators' interactions with the automation change. As system automation increases, the number of tasks that are performed more accurately and reliably than by operators, grows. This has increased operator trust in the automation's ability to perform those tasks. Yet, as this trust grows, their confidence in their own abilities to perform the same tasks manually may decrease (e.g., Lee and Moray, 1992).

Researchers have explored the relationship between automation and operator trust. Parasuraman and Riley (1997) found that as operator trust in the automation grows, they increasingly delegate responsibility for system monitoring to the automation. At the same time, their vigilance and ability to recognize system faults may decrease because their expectation of, and preparedness for, system faults decreases with their growing trust in the automation.

Moray, Inagaki, and Itoh (2000) note that operator trust in a system depends primarily on its reliability. They suggest that with less than about 90% reliability trust in the automation falls off considerably. By contrast, operators' self-confidence in their own ability to operate the system depends not on the system but on their experiences with the system. Paradoxically, the high reliability and accuracy of automation make it more, rather than less, likely that

operators will fail to effectively monitor automated systems as they come to rely on them more and more, and on themselves less and less.

Mosier and Skitka (1996) suggest that the high degree of automation reliability and accuracy can, over time, lead operators to put more faith in automated system guidance than in their own experience and training, and reduce their vigilance. These will lead operators to overlook problems that the automation fails to detect, or to unquestioningly follow the guidance that automation offers, even when the guidance is inappropriate. Mosier and Skitka (1996) refer to this excessive trust and confidence in automation as "automation bias." Operators can over-rely on the automation in highly automated systems, much as team members can over-rely on other operators in their team (see also Mosier, Skitka, Heers, and Burdick, 1998; Skitka and Mosier, 2000).

Bainbridge (1983) and Billings (1997) point out that reliance on automation for monitoring and decision making can erode operator skills, increasing the likelihood of error in the event of a system fault. Bainbridge terms this an "irony of automation" because,

> When manual takeover [of a system] is needed there is likely to be something wrong with the process, so that unusual actions will be needed to control it, and one can argue that the operator needs to be more rather than less skilled, and less rather than more [task] loaded, than average. (p. 272)

An accident that occurred in Columbus, Ohio, in 1994, in which a Jetstream J-41, an automated turboprop airplane, crashed just short of the runway, illustrates how insufficient operator self-confidence and excessive trust in automation can lead to critical errors (National Transportation Safety Board, 1994). At the time of the accident, the weather was poor and visibility limited, conditions that are often quite demanding, thus increasing pilot workload. Each pilot had reason to lack confidence in his own operating skills. The first officer, with little experience operating highly automated aircraft, had only recently been hired. The captain, though experienced in the aircraft, had demonstrated deficiencies in several failed check or examination flights.

The captain had programmed the airplane's flight management computer (FMC) and engaged it to fly the precise flight path to an approach and landing. However, although the FMC could accurately fly a preprogrammed three-dimensional flight path, it controls only the flight path, unlike automation of larger air transport aircraft. On this airplane, the pilots and not the automation control the aircraft's airspeed.

The captain had delegated flight path control to the automation, but then failed to effectively monitor the airspeed. The airplane flew precisely along the flight path, until its airspeed decayed and it experienced an aerodynamic stall. The pilots were unable to recover the airplane. The captain's history of piloting deficiencies contributed to his reliance on the automation. With apparently greater confidence in the airplane's automation than in his own

abilities, he delegated flight path control to the automated flight management system. Although this was not in itself an error, he then failed to adequately monitor the airplane's airspeed, apparently focusing primarily on its flight path, and this failure led to the accident.

The captain's actions on this flight are consistent with Riley's (1996) observations that the reliability of automation itself influences an operator's decision on task assignment. As he observed,

> If the operator had more confidence in his or her own ability to do that task than trust in the automation, the operator was likely to do the task manually, whereas if the operator's trust in the automation was higher than the operator's self-confidence, the operator was likely to rely on the automation. (p. 20)

Team Performance. Researchers have suggested that automation can be considered to be a member of an operator team, altering the role of the team members. Scerbo (1996) argues that an automated subsystem can coordinate activities, be guided by a coach, perform functions without causing harm, provide necessary information when needed, and otherwise perform the types of tasks that human operators typically perform. Paris, Salas, and Cannon-Bowers (2000) contend that automation can replace all or part of team functions, leading to restructured teams and redefined team member roles. As Woods (1996) notes, "introducing automated and intelligent agents into a larger system in effect changes the team composition. It changes how human supervisors coordinate their activities with those of the machine agents" (p. 4).

Automation-Related Errors

New technology can engender changes in complex systems and operator interaction with those systems that, using Reason's (1990, 1997) terms, lead to latent errors or latent conditions that, in turn, create antecedents to operator errors. Although regulators, operators and companies have learned to adapt to automation effects, certain commonalities in automation-related errors have emerged. Operators committing automation-related errors often fail to effectively monitor the systems, or to understand the effects of their actions or those of the automation.

These types of errors were seen in several previously described accidents. In the 1972 accident discussed in Chapter 9, for example, involving the Lockheed L-1011 that crashed in the Everglades, the pilots had engaged the automation to maintain a flight path at a prescribed altitude (National Transportation Safety Board, 1973). Several minutes later they inadvertently disengaged the automation's altitude hold feature and the airplane began to

descend, but they were unaware of this. After delegating flight path control to the automation, they attended to a system anomaly but did not monitor the flight path. They did not realize that the automation had ceased maintaining the selected altitude.

Similarly, in a 1992 accident involving an Airbus A-320 that crashed while on approach to Strasbourg, France (Commission of Investigation, 1994), the pilots established a 3300-foot per minute descent rate, several times faster than a standard descent rate. However, investigators believed that they had actually intended to establish a 3.3° descent angle; a flight path angle that would have corresponded to the actual descent path called for in the approach, unlike the one the aircraft actually flew. As with the L-1011 accident, after programming the flight path the crew failed to monitor a critical aspect of the aircraft's performance, the increasingly rapid descent rate. Although they had established the descent rate through their actions, they did not recognize it and did not attempt to reduce it before the accident.

Case Study

On June 10, 1995, the cruise ship *Royal Majesty*, en route from Bermuda to Boston, Massachusetts, grounded off the United States coast, causing over $7 million in damages to the vessel (National Transportation Safety Board, 1997).

The Navigation System

Early in the voyage a crewmember checked the ship's navigational equipment, a system that included a GPS (global positioning satellite) antenna and receiver, to assure that the ship was following the correct course. The GPS system receives signals from a series of satellites and uses them to derive highly accurate position information. The vessel was also equipped with an integrated bridge system that combined GPS data with other navigation information to steer the vessel along a preprogrammed course, while compensating for wind, current, and sea state. The integrated bridge system displayed the ship's derived position on a video screen in grid coordinates. The operators were confident that the displayed, GPS-derived position was accurate.

The system was designed to automatically default to dead reckoning navigation, a method that did not compensate for wind, current, and sea state, in the event that GPS satellite signals become unavailable. Because it lacks the accuracy of the GPS, dead reckoning requires regular crew attention to ensure that the ship maintains the desired course, unlike GPS-based navigation. In the event that the system defaulted to dead reckoning, the integrated

bridge system would emit a series of aural chirps for one second to alert the crew that it had reverted to the default navigation mode. It would also display on the video screen "DR" for dead reckoning, and "SOL" for solution. The font sizes used for DR and SOL were considerably smaller than those used for the position coordinates.

The crewmembers who used the integrated bridge system, the master, the chief officer, the second mate, and the navigator, had not used this type of system before their assignment to the *Royal Majesty*, and the cruise line had not formally trained them in its use. The ship's officers learned to operate the system by reading the relevant manuals and receiving on-the-job training from an officer experienced in the system.

The Accident

After the ship departed Bermuda, its cable that connected the GPS antenna to the receiver separated. As a result, the integrated bridge system could not receive GPS signals and it defaulted to dead reckoning navigation, as designed. It then continued to navigate and steer the vessel in this mode, but its course began to deviate from the intended one, until the vessel grounded 17 miles off course.

Investigators identified several errors that the watch officers, responsible for monitoring the vessel and its course, had committed. The officers did not understand the "DR" and "SOL" messages that the system displayed, and had not attempted to learn their meaning. Therefore, they did not recognize that the system had ceased to receive GPS data for navigation and course control and they were unaware that it had defaulted to the less accurate dead reckoning method. Although they had regularly checked the bridge system's display to confirm that the vessel was following the programmed course, they did not verify that the course that was displayed corresponded to the programmed one.

If the system had been navigating by GPS, the programmed and the actual course would have matched. However, because of the limitations of dead reckoning, without crew intervention the courses were likely to diverge when the system used that navigation method, and the vessel increasingly deviated from its intended course.

Investigators determined that several aspects of the crew's use of the automation led to their errors, and that the automation had fundamentally affected the crewmember roles. As they conclude (National Transportation Safety Board, 1997),

> Bridge automation has also changed the role of the watch officer on the ship. The watch officer, who previously was active in obtaining information about the environment and used this information for controlling the ship, is now "out of the control loop." The watch officer is relegated to passively monitoring the status and performance

> of the automated systems. As a result…the crewmembers of the *Royal Majesty* missed numerous opportunities to recognize that the GPS was transmitting in DR mode and that the ship had deviated from its intended track.
>
> [Further,] the watch officers on the *Royal Majesty* may have believed that because the GPS had demonstrated sufficient reliability for 3½ years, the traditional practice of using at least two independent sources of position information was not necessary.
>
> Notwithstanding the merits of advanced systems for high-technology navigation, the Safety Board does not consider the automation of a bridge navigation system as the exclusive means of navigating a ship, nor does the Board believe that electronic displays should replace visually verifiable navigation aids and landmarks. *The human operator must have the primary responsibility for the navigation*; he must oversee the automation and exercise his informed judgment about when to intervene manually. (Emphasis added, pp. 34 and 35)

Summary

Automation, the replacement of tasks by automated system components that operators had previously performed themselves, has both enhanced and degraded system safety. Many aspects of automation have affected the role of the operator, but some have created unique antecedents to error. Automation's high reliability and accuracy can lead operators to excessively rely on it, degrading their vigilance and system monitoring skills. As operators repeatedly experience the beneficial aspects of automation, they may delegate tasks to it without proper monitoring to ensure that the system performs as directed.

Some operators have demonstrated greater trust in the abilities of the automation to control the system than in their own abilities. This may lead to their unquestioning acceptance of automation guidance, or to overlook problems that the automation has failed to detect.

DOCUMENTING AUTOMATION-RELATED ERRORS

- Evaluate automated system displays and controls in accordance with criteria listed in Chapter 4.
- Describe the specific functions the automated system, its capabilities in system monitoring and control, and the nature of its presentation of system-related data.

- Identify the operator's experience with automated systems, including the length of time operating the systems, and the level or extent of automation the operator typically was familiar with when operating the system.
- Document the tasks the automation performs, its information sources, the results of its information processing, and the level of operator input and control over these tasks.
- Record operator actions and decisions involving automation, and the type of automation-related error(s) committed.
- Describe the tasks that the operators delegated to the automation, and the extent to which the operators monitored critical system parameters.
- Examine the company's training and procedures in automation use, and interview and observe operators, if possible, to learn the practices that they employed with regard to automation-related interactions.

References

Aeronautica Civil of the Government of Colombia. 1996. *Aircraft accident report, controlled flight into terrain*. American Airlines Flight 965, Boeing 757-223, N651AA, near Cali, Colombia, December 20, 1995. Bogotá, Colombia.

Amalberti, R. R. 1998. Automation in aviation: A human factors perspective. In D. J. Garland, J. A. Wise, and V. D. Hopkin, (Eds.), *Handbook of aviation human factors* (pp. 173–192). Mahwah, NJ: Erlbaum.

Bainbridge, L. 1983. Ironies of automation. *Automatica*, 19, 775–779.

Billings, C. E. 1997. *Aviation automation: The search for a human-centered approach*. Mahwah, NJ: Erlbaum.

Commission of Investigation. 1994. *Final report of the investigation commission into the accident that occurred on 20 January 1992, near Mont Sainte-Odile (Bas-Rhin), to Airbus A-320, Registration F-GGED, operated by Air Inter*. Paris, France: Minister of Equipment, Transport and Tourism.

Degani, A., Shafto, M., and Kirlik, A. 1999. Modes in human-machine systems: Constructs, representation, and classification. *International Journal of Aviation Psychology*, 9, 125–138.

Endsley, M. R. and Kaber, D. B. 1999. Level of automation effects on performance, situation awareness, and workload in a dynamic control task. *Ergonomics*, 42, 462–492.

Endsley, M. R. and Kiris, E. O. 1995. The out-of-the-loop performance problem and level of control in automation. *Human Factors*, 37, 381–394.

Jamieson, G. A. and Vicente, K. J. 2005. Designing effective human-automation-plant interfaces: A control-theoretic perspective. *Human Factors*, 47, 12–34.

Kantowitz, B. H. and Campbell, J. L. 1996. Pilot workload and flightdeck automation. In R. Parasuraman and M. Mouloua, (Eds.), *Automation and human performance: Theory and applications* (pp. 117–136). Mahwah, NJ: Erlbaum.

Lee, J. and Moray, N. 1992. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35, 1243–1270.

Molloy, R. and Parasuraman, R. 1996. Monitoring an automated system for a single failure: Vigilance and task complexity effects. *Human Factors*, 38, 311–322.

Moray, N., Inagaki, T., and Itoh, M. 2000. Adaptive automation, trust, and self-confidence in fault management of time-critical tasks. *Journal of Experimental Psychology: Applied*, 6, 44–58.

Mosier, K. L. and Skitka, L. J. 1996. Human decision makers and automated decision aids: Made for each other? In R. Parasuraman and M. Mouloua, (Eds.), *Automation and human performance: Theory and application* (pp. 201–220). Mahwah, NJ: Erlbaum.

Mosier, K. L., Skitka, L. J., Heers, S., and Burdick, M. 1998. Automation bias: Decision making and performance in high-tech cockpits. *International Journal of Aviation Psychology*, 8, 47–63.

National Transportation Safety Board. 1973. Aircraft accident report, Eastern Air Lines, Inc., L-1011, N310EA, Miami, Florida, December 29, 1972. Report Number: AAR-73-14. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1980. Aircraft Accident Report, Aeromexico DC-10-30, XA-DUH, over Luxembourg, Europe, November 11, 1979. Report Number: AAR-80-10. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1986. Aircraft Accident Report, China Airlines Boeing 747-SP, N4522 V, 300 Nautical Miles Northwest of San Francisco, California, February 19, 1985. Report Number: AAR-86-03. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1994. Aircraft Accident Report, Stall and Loss of Control on Final Approach, Atlantic Coast Airlines, Inc. United Express flight 6291 Jetstream 4101, N304UE Columbus, Ohio January 7, 1994. Report Number: AAR-94-07. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1997. Marine Accident Report, Grounding of the Panamanian Passenger Ship *Royal Majesty* on Rose and Crown Shoal near Nantucket, Massachusetts, June 10, 1995. Report Number: MAR-97-01. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 1998. *In-Flight Icing Encounter and Uncontrolled Collision with Terrain, Comair Flight 3272, Embraer EMB-120RT, N265CA*. Report Number AAR-98-04. Washington, DC: National Transportation Safety Board.

Norman, D. A. 1981. Categorization of action slips. *Psychological Review*, 88, 1–15.

Norman, D. A. 1988. *The Psychology of Everyday Things*. New York, NY: Basic Books.

Norman, D. A. 1990. The problem of automation: Inappropriate feedback and interaction, not over-automation. *Philosophical Transactions of the Royal Society of London, B*, 327, 585–93.

O'Hanlon, J. F. 1981. Boredom: Practical consequences and a theory. *Acta Psychologica*, 49, 53–82.

Parasuraman, R. 2000. Designing automation for human use: Empirical studies and quantitative models. *Ergonomics*, 43, 931–951.

Parasuraman, R., Mouloua, M., Molloy, R., and Hilburn, B. 1996. Monitoring of automated systems. In R. Parasuraman, and M. Mouloua, (Eds.), *Automation and human performance: Theory and applications*. Mahwah, NJ: Erlbaum.

Parasuraman, R. and Riley, V. 1997. Humans and automation: Use, misuse, disuse and abuse. *Human Factors*, 39, 230–253.

Parasuraman, R., Sheridan, T. B., and Wickens, C. D. 2000. A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans*, 30, 286–297.

Paris, C. R., Salas, E., and Cannon-Bowers, J. A. 2000. Teamwork in multi-person systems: A review and analysis. *Ergonomics*, 43, 1052–1075.

Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Riley, V. 1996. Operator reliance on automation: Theory and data. In R. Parasuraman, and M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 19–35). Mahwah, NJ: Erlbaum.

Sarter, N. B. and Woods, D. D. 1995. How in the world did we ever get into that mode? Mode error and awareness in supervisory control. *Human Factors*, 37, 5–19.

Sarter, N. B. and Woods, D. D. 1997. Team play with a powerful and independent agent: Operational experiences and automation surprises on the Airbus A-320. *Human Factors*, 39, 553–569.

Sarter, N. B. and Woods, D. D. 2000. Team play with a powerful and independent agent: A full-mission simulation study. *Human Factors*, 42, 390–402.

Scerbo, M. W. 1996. Theoretical perspectives on adaptive automation. In R. Parasuraman and M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 37–63). Mahwah, NJ: Erlbaum.

Sheridan, T. B. and Parasuraman, R. 2005. Human-automation interaction. *Reviews of Human Factors and Ergonomics*, 1, 89–129.

Skitka, L. J. and Mosier, K. L. 2000. Automation bias and errors: Are crews better than individuals? *International Journal of Aviation Psychology*, 10, 85–97.

Wiener, E. L. 1989. *Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft*. NASA Contractor Report 177528. Moffett Field, CA: NASA Ames Research Center.

Wiener, E. L. and Curry, R. E. 1980. Flight-deck automation: promises and problems. *Ergonomics,* 23, 995–1011.

Woods, D. D. 1996. Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman and M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 3–17), Mahwah, NJ: Erlbaum.

Woods, D. D., Johannesen, L. J., Cook, R. I., and Sarter, N. B. 1994. *Behind human error: Cognitive systems, computers, and hindsight*. Wright-Patterson Air Force Base, OH: Crew Systems Ergonomics Information Analysis Center (CSERIAC).

16

Case Study

Introduction

Many errors and their antecedents have been examined in this text, and numerous accidents were cited to illustrate the nature of the errors that led or contributed to those accidents. One accident in particular demonstrates several points about errors in complex systems. This accident also describes challenges that investigators could face, highlights the data gathering and analysis processes used to identify critical errors and their antecedents, and identifies recommendations that investigators can suggest to remediate system deficiencies highlighted in an investigation.

The Accident

On July 6, 2013, a Boeing 777-200ER crashed while on approach to San Francisco International Airport, destroying the aircraft and injuring 52 of those onboard, three of them fatally (National Transportation Safety Board, 2014). The flight originated in Inchon, South Korea, destined for San Francisco. The airplane was later found to have been flying at an airspeed of 110 knots when it struck the edge of the runway, about 20 knots slower than it should have been at that point. Only seconds before the accident, when it was too late to avoid it, the pilots recognized the low speed. Up to that point they had not noticed that the autothrottle mode they had selected had changed and it was no longer maintaining the selected airspeed. Investigators determined that the accident was caused, in part by "the flight crew's inadequate monitoring of airspeed" (p. 129).

Airspeed control, with that of altitude and position, is critical to safe flight. Only minimal variations from the appropriate speed (based on flight phase, airplane weight, and atmospheric conditions) are acceptable at any point in the flight, but especially on approach and landing when even small variations from the appropriate airspeed can be catastrophic. Airspeeds even a few knots too slow can lead to an aircraft stall and/or excessive descent rate.

Background

After investigators read out the airplane's flight data recorder and determined that the airplane's airspeed was too slow while on approach to the runway, they determined that the slow airspeed could have been due to only one of two possible causes, an airplane-related failure, either in its engines, engine-related systems, or in the autothrottle/autopilot system that maintained the pilot's selected airspeed, or a pilot error in either failing to monitor and correct the slow airspeed or to select the proper airspeed for the approach.

At the accident site investigators quickly examined the engines and found that the internal engine damage in both engines was consistent with that of engines producing power at the time of impact; therefore, they determined that the B-777's engines had not failed before the accident (Figures 16.1 and 16.2). Investigators, reading the flight recorders and other sources of data, found that the pilots had entered the appropriate airspeed into the autothrottle and the autothrottle had performed as designed. Thus, an airplane-related anomaly was ruled out and the focus then centered on the pilots' performance, including their training and understanding of the autothrottle system, company procedures on autothrottle use and monitoring, and on the design of the airplane's automated systems. Given the criticality of airspeed to flight safety, the issue of how pilots could lose airspeed awareness on landing became critical. Pilots are taught, from the very beginning of their flight training, to maintain close control of airspeed and to tolerate minimum variation in airspeed through all flight phases but especially during takeoff, climb, and approach and landing.

Moreover, commercial airplane accidents are rare events that receive considerable attention. Airlines, regulators, and airframe and engine manufacturers study each major accident and as investigators' findings are announced, modify their training, procedures, advisories to customers or pilots, or oversight, as necessary and as appropriate to minimize the likelihood that accidents and associated operator errors are repeated. The industry's implementation of accident investigation lessons is one factor making the worldwide accident rate as low as it has become.

Yet, before this accident, several previous accidents had occurred in which the pilots of autothrottle-equipped aircraft, that is, aircraft with automated systems that monitored and controlled airplane airspeed, lost airspeed awareness on landing. Almost 30 years before this accident a DC-10 touched down in New York at an airspeed 30 knots too fast, destroying the airplane and leading to 12 passenger and crewmember injuries (National Transportation Safety Board, 1984). Further, about 3 years before the San Francisco accident, a highly automated airplane was at too low an airspeed on its approach to Amsterdam. Nine passengers and crew were killed and the airplane was destroyed when the airplane struck the ground about a mile short of the

FIGURE 16.1
The impact point of the B-777 at the seawall, just before runway at San Francisco International Airport. Wreckage debris path continued onto the runway. (Courtesy of the National Transportation Safety Board.)

FIGURE 16.2
Aerial view of the B-777 wreckage at San Francisco International Airport. The airplane came to a stop beyond the end of the runway. The damage to the tail suggests that the airplane's tail struck the ground first. (Courtesy of the National Transportation Safety Board.)

runway (Dutch Safety Board, 2010). At too high an airspeed on approach and landing an air transport airplane will likely to be unable to be brought to a stop on the runway; at too low a speed, the airplane will likely stall or descend too rapidly into the runway. Despite these accidents involving failure to monitor airspeed, and considerable research on the potential hazards of operator interaction with highly automated systems, the pilots of the B-777 allowed the airspeed to deteriorate to the point that the airplane descended rapidly and struck a seawall at the edge of the runway (the runway had been partially extended into San Francisco Bay).

The Evidence

The aircraft's engines and systems were found to have worked as designed. Further, flight data recorder parameters, including a variety of engine performance, airspeed, and vertical speed data, demonstrated that the airplane's airspeed was too low and its vertical speed, that is, its descent rate, too fast in the moments before the accident. Given the absence of a pre-impact flaw with the engines and systems, investigators examined the performance of the two pilots who served as pilot flying and pilot monitoring during much of the flight, particularly on takeoff and on approach and landing. They looked at their background, training, company procedures with regard to approach and landing airspeed control, and the design of the interface between autothrottle and pilot.

The Pilots

The pilot flying, serving as the captain on this flight, was not the pilot in command (as will be discussed shortly). He was 45 years old and had begun employment with the airline in an "ab initio" program designed to train people with no flight experience to become pilots at the airline. At the time of the accident he was rated in the Airbus A-320, the Boeing 737, 747-400, and the Boeing 777. He had a total of 9,684 total flight hours, including 3729 hours as pilot in command or captain, experience suggestive of an experienced pilot, albeit not in the B-777.

He began his training to serve as a Boeing 777 captain about 6 months before the accident, and had successfully qualified as captain, accumulating 33 hours of flight time and 24 hours of simulator time at the time the accident. Before that he had served as captain on the A-320 for just over 5 years. Aviation regulations require air transport pilots to complete a period of supervised flight to qualify to fly in their respective positions unsupervised, what is referred to as initial operating experience or IOE. In Korea, this requirement called for pilots to fly 20 flight legs for a minimum of 60 flight hours.

The captain had completed 8 flight legs and 33 hours 31 minutes of IOE flight before the accident flight. All of the landings on those flights involved instrument landing system approaches, in which the airplane is flown according to precise vertical and lateral guidance. On this flight however, the approach in use was a visual approach, and the pilots were so informed; equipment providing precise vertical runway guidance was out of service. In modern aircraft, the autothrottle and autopilot can replicate the guidance needed to accurately fly visual approaches by applying internal airplane models of both vertical and lateral guidance, provided the pilots enter the necessary flight data into the system and closely monitor the approach to ensure that it remains within the necessary flight parameters.

Investigators interviewed three training captains who had observed the captain on IOE flights in the Boeing 777. One said that the errors the captain made in the IOE were consistent with those of a pilot at that stage of the IOE, while another reported the pilot was “above average” in his IOE ride. By contrast, the third told investigators that (National Transportation Safety Board, 2014),

> The PF [pilot flying] was not well organized or prepared, conducted inadequate briefings, poorly monitored the operation, and deviated from multiple standard operating procedures (SOP). He said that the PF allowed the descent rate to get a little high on short final and allowed the nose to drop at an altitude of 200 to 100 ft. This had caused the airplane to go below the desired glidepath and forced the PF to initiate the flare early. The [instructor pilot or training captain] IP was not overly concerned, however, because he knew that the PF had to complete more OE [IOE] flights. (p. 15)

The monitoring pilot was 49 years old with a total of 12,307 hours of flight experience, 9045 of those as pilot in command, and 3208 hours of those hours in command of a Boeing 777. On the accident flight he was acting as first officer but serving as the training captain supervising the pilot in his IOE, and was the pilot in command of the flight. He began his career as a pilot in the Korean Air Force, and had been flying the Boeing 777 for over 5 years, all of them as captain. He had qualified as a training captain about 2 months before the accident. The accident flight was his first flight in which he served unsupervised as a training captain. Pilots who had trained the training captain in that role, or who had observed him training in that role, spoke favorably of his performance and qualifications to serve as a training captain.

Investigators documented the local times (i.e., in Korea) that the two pilots went to sleep and got up in the days preceding the accident flight. They determined that the pilots were likely fatigued at the time of the accident because of the nature of the flight itself, including the fragmented nature of sleep the pilots received in the 24 hours before the flight, given the times slept in their rest periods during the flight, and the time of day, corresponding to

early morning according to the pilots' local time, when they would ordinarily have been deeply asleep. Research has found an association between performance in the early morning hours and a higher than expected error and accident rate (e.g., Lenne, Triggs, and Redman, 1997).

The Approach to San Francisco

According to investigators, the critical crew errors that led to the accident began less than 5 minutes before impact, when air traffic control directed them to slow the airplane to 180 knots from 210 knots, and to maintain that speed until 5 miles from the runway. At that point the aircraft was about 14 (nautical) miles from the runway. The pilot flying slowed the airplane using its autopilot system, entering the 180 knot speed into the autopilot/autothrottle system and executing it in the automated system to maintain that airspeed. However, the autopilot responded by raising the nose of the airplane, the preferred technique to reduce airspeed, but not by reducing the thrust. This reduced the airspeed as directed, but its vertical speed was increased as the airplane began to climb. Neither pilot noticed the airplane's deviation from the desired vertical flight path, although investigators pointed out that the information was displayed in the airplane's navigation display informing them of the climb.

Eleven and a half miles from the runway the flying pilot entered a descent rate into the autopilot system, in an effort to descend. Shortly thereafter, he asked the pilot monitoring, the check pilot serving as the monitoring pilot on this flight, to lower the landing gear. Three seconds later, about 3 minutes before the airplane struck the edge of the runway, the monitoring pilot told the flying pilot, "this seems a little high," an English translation of the Korean language the pilots used when communicating among themselves (communications with U.S. air traffic controllers were in English). The flying pilot, after some initial discussion with the monitoring pilot, increased the descent rate to 1500 feet a minute, then reduced it back to 1000 feet per minute at 6.3 miles from the runway. The airspeed was then 178 knots and the airplane was several hundred feet above the intended height.

At this point the pilots began performing another element of instrument approach flying, preparing for a missed approach. A missed approach, in which the pilots cease conducting the approach and fly away from the airport, is necessary if the controllers cancel a landing clearance, the airplane is not properly aligned for a landing, or other reasons. To ensure that the airplane climbed to the appropriate altitude in the event that the crew needed to execute a missed approach, the pilot flying began to review the missed approach procedure for that runway. He informed the pilot monitoring that the missed approach altitude was 3000 feet, an altitude higher than the airplane's altitude at that point. Shortly thereafter, the pilot entered 3000 feet into the autopilot as the selected altitude.

At 5 miles from the runway the flight was about 400 feet above the desired altitude but below 3000 feet altitude. The pilot flying changed the autothrottle

mode in an effort to increase the descent rate, and also changed the target airspeed in the autothrottle mode to 152 knots. He asked the monitoring pilot to extend the flaps from 5° to 20°, as required at that point on the approach. However, the target airspeed was about 20 knots slower than the airplane's speed at that point, and the selected altitude was higher. As a result, the autopilot raised the nose of the airplane to climb to the selected 3000 foot altitude while the autothrottle increased engine thrust. The flying pilot immediately recognized the change in thrust and in pitch and overrode the autothrottle by manually moving the thrust levers to idle, and pushed the control column down to lower the nose. However, neither pilot was aware that manually reducing the thrust and overriding the autothrottle changed the autothrottle mode from the one they had selected to one in which it no longer controlled the airspeed. The mode change was not signaled by an aural alert; rather, it was identified by a change in the identity of the mode displayed in a panel in front of the pilots. The pilots, who were not looking at that display were unaware of both the autothrottle mode change and its effects on speed control. They did not know that that the autothrottle was no longer controlling the airspeed.

About a minute from impact the airspeed was still higher than desired. The flying pilot then changed the target autothrottle speed to 137 knots, the speed desired for landing. Informal airline guidance called for pilots, when flying visual approaches, to disengage both pilots' flight directors at that point. On the B-777 the flight directors, instruments that provide information on controlling the control columns, also affect autothrottle mode. Airline guidance called for pilots to disengage both flight directors, one for each of the two pilots, and then reengage only the first officer's flight director. Disengaging both flight directors causes the autothrottle mode to default to the one most recently engaged, in this case the one the flying pilot had selected that maintained the airspeed. However, the first officer's flight director was not disengaged, only the pilot flying's flight director. As a result, the autothrottle remained in the mode in which it was operating, in this case a mode that no longer controlled airspeed.

The airplane reached the selected airpseed of 137 knots but shortly thereafter one of the two observer pilots in the cockpit called out "it's high." After the pilot monitoring called out that the airplane was 1000 feet above the ground, the observer pilot called out "sink rate." The flying pilot responded "yes sir." Six seconds later the observer pilot again called out "sink rate, sir." Ten seconds later air traffic control cleared the aircraft to land and, about 30 seconds before impact, one of the pilots reiterated the landing clearance and announced that the landing checklist had been completed, that is, all the landing tasks performed. About 10 seconds later one of the pilots, presumably the monitoring pilot said, "it's low" to which the other pilot responded "yeah." About 10 seconds later, 8 seconds before impact, a pilot said "speed," repeating it 2 seconds later. The sound of the stick shaker, a device in the control column that provides both tactile and audio cues of an impending aerodynamic stall, alerted. Three seconds before impact a pilot ordered "go

around," but at that point the airplane's descent could not have been arrested. It struck the edge of the runway 3 seconds later.

The Error

By continuing to fly the approach while attempting to both slow the airspeed and have the airplane descend from its height above the desired vertical path, the pilots added to what was already the highest workload phase of their flight, approach and landing. Because aircraft operate in three dimensions, particular preparation is needed when flying an air transport aircraft on approach to landing to ensure that it is flying within narrowly acceptable parameters along the three dimensions. Not fully establishing the necessary airspeed and flight path parameters on approach to landing can challenge the best pilots to bring the airplane back to acceptable (or what as referred to as "stabilized") flight in the remaining time available before landing. That is, trying to both slow the airplane while attempting to descend it on the vertical profile, and maintain the appropriate lateral course to the center of the runway, becomes more difficult closer to the runway, when the tolerance for exceeding vertical and lateral flight parameters becomes increasingly small. This is especially true when precise vertical guidance is unavailable, as the pilots' had been informed The pilots' failure to stabilize the airplane's airspeed, vertical speed, and flight path when initiating the approach created a situation in which (1) they were unable to bring the airspeed and descent rate to acceptable limits and (2) their workload increased to the point where they could not devote the attention needed to fully monitoring necessary aspects of the flight. At the same time, their lack of complete understanding of the automation exacerbated the difficulties that they themselves had created in controlling the airplane. Fully delegating airspeed control to the automation is acceptable so long as the airspeed is monitored and pilots are prepared to quickly retake control if needed. However, the research on automation indicates that operators will likely delegate control to automation when their workload is high, as occurred in this accident. However, as Bainbridge (1983) might have pointed out, an irony of automation is that by fully delegating and not monitoring automation the operator removes himself or herself from automation oversight during operating phases such as this, when monitoring is most needed.

The pilots' major error, their failure to monitor airspeed, concerns a flight parameter that, with altitude and vertical speed, pilots must be aware of and control, especially during climbs and descents. The antecedents to the pilot errors, while compelling, should still not have prevented the pilots from monitoring airspeed during approach. Regardless of workload or lack of knowledge of the autothrottle system, the fundamental training that all pilots undergo to monitor airspeed on approach and landing is not excused

by these antecedents. Rather, identifying the antecedents allows investigators to explain the errors and understand how they came about. Although other errors preceded this one, for investigative purposes, the critical antecedents to this single error were the pilots' self-created workload and lack of understanding of the autopilot/autothrottle. The latter resulted from a combination of

- Operator experience
- Operator fatigue
- Airplane system complexity and automation opacity
- Manufacturer information about its automated system
- Automation training
- Company automation policy

Antecedents to Error

In this, as in other accidents, a unique interaction of antecedents led to the key pilot error. These were the pilot's incomplete knowledge and misunderstanding of the airplane's automation capabilities, a result of manufacturer shortcomings in its automation design and in the information it provided to airlines operating the 777. These combined with several pilot/airline factors including, inexperience in flying visual approaches, and in the pilots' respective roles on the airplane, effects from previous experience on an airplane with a similar, but yet critically different stall protection system as the B-777, and the airline's policy on automation use. Finally, the pilot's error in not disengaging both flight directors contributed to the pilots' error. The pilots believed that the autothrottle would maintain airspeed regardless of other pilot actions; consequently, they focused their monitoring on flight path and did not monitor airspeed.

Investigators noted that the pilots were required, no later than when reaching 5 miles from the runway, to discontinue an approach if the airplane was not within acceptable flight path and speed parameters. The effects of the pilots' continuing the approach while attempting to stabilize the flight path and conform to the approach requirements created a workload that increased the closer the airplane was to the runway. As the airplane neared the runway there was less time available to bring both speed parameters to acceptable levels, while speed, altitude, and descent rate tolerances narrowed. The resultant workload precluded the pilots' ability to monitor the airspeed effectively. By contrast, discontinuing the approach, though not a critical error, would have reflected poorly on both pilots, in particular the pilot flying who was still not qualified to fly the airplane unsupervised and may have needed additional observation time had he done so. Investigators

suggested that this knowledge may have encouraged the pilots to continue the approach despite the approach being unstabilized.

Operator Antecedents: Experience

The pilots were both experienced in air transport operations, with the monitoring pilot an experienced Boeing 777 captain in addition to his extensive flight experience. However, both pilots were inexperienced in several elements critical to this accident. The captain, or pilot flying, was new to the Boeing 777 and was still under instructor pilot observation. All of the eight B-777 landings he had conducted were under supervision, and the approaches were all instrument landing system approaches, which provided precise vertical and lateral flight path guidance. The accident flight was his first attempt in the B-777 to execute a non-precision approach, an approach that is rare in air transport operations. The two types of B-777 inexperience, in the airplane in general and in flying a visual approach in particular, served as an antecedent to his error of initiating, and then maintaining an approach with both the airspeed and the vertical speed, at different points in the approach, outside of acceptable parameters.

Further, the pilot flying's experience may well have interfered with his understanding of the B-777's automation system, and thus served as an antecedent to his errors. His previous airplane experience was on an Airbus-A-320. Although both airplanes are considered highly automated, equipped with full autopilot/autothrottle systems, the A-320, unlike the B-777, has a protection designed to prevent an airplane from entering a stall, a protection that can only be disengaged by a specific pilot action. Further, his more recent training on the B-777 included a presentation on a stall protection system on the B-777, a protection system that, unlike the other airplane, could be disengaged without explicit pilot action. Investigators suggested that his recent experience on an airplane with a stall protection that remained active in the absence of specific pilot action may have interfered with his airspeed monitoring on the B-777, in the mistaken belief that the autothrottle would continue to offer stall protection throughout the flight.

The instructor pilot, serving as the pilot monitoring and as first officer, was conducting his first unsupervised observation flight. A critical element of an instructor pilot's responsibilities is being cognizant of the performance of the pilot under observation, and recognizing both when it is appropriate to call the flying pilot's attention to flight parameters and when it is necessary to take control of the airplane when flight safety is considered at risk. Commenting at an inopportune or inappropriate time, or taking airplane control unnecessarily, considered an extreme act, can negatively affect pilot performance and be counterproductive. On the other hand, not commenting on pilot actions or decisions when necessary can contribute to poor pilot performance, and delaying taking airplane control when called for can compromise flight safety. Allowing pilots to make mistakes is an effective way to

promote learning; but also recognizing when flight safety is at risk is a key to being an effective flight instructor. The instructor serving as the pilot monitoring on this flight erred in both respects, he did not call the pilot flying's attention to the deteriorating airspeed until late in the approach, and did not take control of the flight when flight safety was endangered.

Operator Antecedents: Fatigue

Both pilots were also fatigued from the duration of the flight, and by the time of day at which the accident occurred. The pilots were scheduled to report for duty at 1510 local time and depart over an hour later. The accident occurred at 1127 San Francisco time, or 0327 Korean time, a time that corresponds to what has been demonstrated to be a low point in people's sleep. Despite the fact that they rested on the airplane, with the pilot flying and pilot monitoring sleeping about 2 and 3 hours, respectively, during the approximately 10 ½ hour flight, investigators concluded that their disrupted sleep and the effects of time of day on their circadian rhythms, led to their being fatigued. As investigators concluded, "all three pilots were likely experiencing some fatigue at the time of the accident, and each made errors that were consistent with the effects of fatigue" (National Transportation Safety Board, 2014, p. 86).

Equipment Antecedents: Airplane System Complexity and Automation Opacity

The pilot flying was unaware that when reducing the thrust to idle, the autothrottle would change its operating mode from one that actively maintained the pilot-selected airspeed to one, called "hold," in which it was disengaged from airspeed control. Investigators focused on what contributed to the pilots' lack of familiarity with this automation feature, and why they nevertheless did not notice that the airspeed decreased to where it was below a safe speed, despite their extensive training and their demonstrated knowledge of the airplane's autopilot and autothrottle systems.

On the Boeing 777 and other modern air transport aircraft, the autothrottle, autopilot, and flight directors are interconnected; input into one can affect the others. The airline's B-777 pilots were informed, in their training on the airplane and in the airline's flight manual (which they were required to review and whose key points they were required to master) of how the autothrottle mode changed, either through direct pilot input or through interaction with another feature of the automation, and how these mode changes were displayed to the pilots. The automated modes were presented on a flight display panel in front of each pilot. To recognize that the modes changed the pilots had to look at a display and know the mode and understand its effects on flight control. However, the display was outside the expected visual scan of a pilot flying an approach; without an aural alert in the event pilots' workload

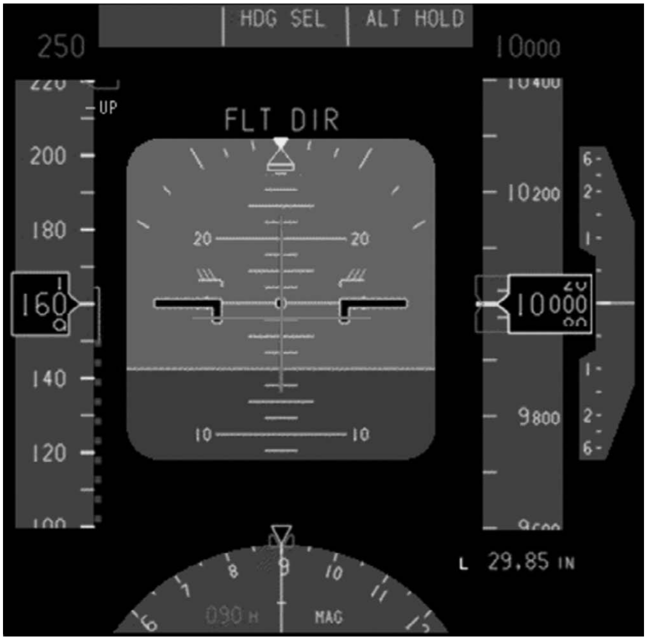

FIGURE 16.3
Primary flight display on Boeing 777. Airspeed at left column in bracket, vertical speed in right-most column, with automation mode presented in green at top. Autothrottle mode (top center box, left of HDG SEL) not displayed, only Heading Select (autopilot flight director roll mode) and Altitude Select (autopilot flight director pitch mode) displayed. (Courtesy of the National Transportation Safety Board.)

was high, or if distracted, his or her ability to notice the change would be reduced (Figure 16.3).

The pilots' error of not fully disengaging both flight directors and then reengaging the first officer's (or pilot monitoring on this flight) flight director, also was committed despite the airline's flight crew training manual directing pilots to do so when "intercepting the visual profile," that is, established on the vertical path in the visual approach. Disengaging the flight directors caused the autothrottle to change to a default mode that would have maintained airspeed control. However, the airline did not explain to their pilots the reason for disengaging both flight directors and reengaging one when conducting a visual approach. The pilots' failure to recognize that the mode had changed occurred independently of a pilot action. The mode change was precipitated, to some extent, by their failure to disengage both flight directors and reengage one, as well as the flying pilots' reducing the thrust to idle while on the approach. The combination of high workload and lack of transparency regarding the reason for flight director disengagement–reengagement, partially led to this error. The error then contributed to the disengagement of the autothrottle in the absence of specific pilot action to do so.

Equipment Antecedents: Equipment Information

The Boeing 787 and the Boeing 777 autothrottles shared a similar feature; it did not “wake up” or reengage if, when in the thrust “hold” mode (the mode that the autothrottle defaulted to when the flying pilot reduced the thrust on approach), the airspeed decayed to less than that selected. However, investigators learned that during the 787 certification flights, where the regulator, the Federal Aviation Administration determines the extent to which a new airplane meets requirements needed to be approved for flight, a Federal Aviation Administration test pilot, who had been unaware of this feature, recognized and commented to the agency on its adverse safety characteristics. In response, Boeing added to its 787 airplane flight manual the notice, “When in HOLD mode, the autothrottle will not wake up even during large deviations from target speed and does not support stall protection.” However, the notice, which was sent to all 787 users, was not sent to 777 users, despite its having the same feature (the B-777 flight manual had been approved without it and thus, there was no “requirement” that users be so informed after the fact). Consequently, unless airlines changed their flight manuals on their own, or their pilots learned of the issue informally, 777 pilots were unaware that the autothrottle would not reengage and maintain airspeed control if operating in the hold mode. Investigators learned that the pilot flying was unaware of this feature, believing instead that the autothrottle would maintain pilot selected airspeed through all phases of flight when he engaged it.

Company Antecedents: Automation Policy

The airline contributed an antecedent by suggesting to its pilots, through a simulator demonstration, that the autothrottle would maintain the selected airspeed. The demonstration showed that with both autothrottle and autopilot disengaged, reducing thrust to idle and allowing the airspeed to reduce to below minimum speed (as shown on the airplane’s airspeed display), the autothrottle would “wake up” and increase thrust to return airspeed to minimum maneuvering speed. It suggested to pilots that the airplane’s airspeed would remain active through all phases of flight, and that they could rely on it to maintain the necessary speeds. Of course, without knowledge of the “hold” mode feature of not responding to critically slow airspeed, the airline could not have known that its demonstration to its pilots was based on erroneous information.

The airline’s policy also encouraged its pilots to fully use the airplane’s automation during approach and landing. The airline’s B-777 chief pilot told investigators that the airline recommended using as much automation as possible when flying the airplane. By contrast, many airlines encourage their pilots to disengage the automation and control the airplane manually during approach and landing, primarily to enable them to retain their

manual flying skills during flight phases when these skills are most needed, and to keep pilots fully in the loop of aircraft control during approach and landing flight phases. The airline's encouragement of automation use, while not in and of itself an antecedent to the pilots' error, failed to take into account that extensive reliance on automation can, over time, diminish operator skills when the automation is not acting as expected. As described previously, a system that consistently performs accurately and reliably will, over time, subtly influence operators' oversight of that system and can lead an operator to fail to notice system anomalies in the event they occur. The company's promotion of automation exacerbated the effects of the pilots' mistaken pilot belief that the B-777 airspeed would not deteriorate to below a safe speed.

Figure 16.4 demonstrates the relationship of the operator, manufacturer, and company antecedents to the pilots' error of not monitoring the airspeed.

Operator antecedents

- Created high workload condition by not stabilizing airspeed and vertical speed during final approach
- Individually inexperienced in critical performance skills
- Did not fully disengage and reengage flight directors
- Fatigue

↓

Manufacturer antecedents

- Visual presentation only of operating mode with no aural indication of autothrottle mode change
- Opaque autothrottle mode change independent of direct pilot action
- Did not inform operators that one autothrottle operating mode was disengaged from airspeed control
- Opaque relationship between flight director and autothrottle mode

↓

Company antecedents

- Created the impression to pilots that autothrottle continuously maintains pilot-selected airspeed
- Encouraged pilots to use only automation while flying on final approach

FIGURE 16.4
The antecedents that led to the pilots' failing to monitor airspeed on approach to landing.

The individual antecedents to error in this accident can be attributed largely to several factors operating together: automation design, training, and airline policies that combined to adversely affect pilot performance once they had created a high workload situation during the approach. It is possible, if not likely, that this combination of antecedents would not have led to the pilots' error had the antecedents been present during a routine operating phase. However, during a phase of unusually high workload, with a pilot flying who had never before flown this airplane on an approach that lacked precise vertical path guidance, and with an observation pilot relatively inexperienced in recognizing when he needed to take action to avoid a safety-related flight issue, the combination of circumstances allowed the antecedents to adversely affect the pilots' performance.

Antecedents and Errors

Relationships between Antecedents and Errors

In Chapter 3, the determination of antecedents was described as based on research supporting the analysis. In this accident considerable research on automation use, operator trust in automation, and operator awareness of mode changes supported the investigators' conclusions. Further, investigators attempted to answer two questions to enable them to determine whether the relationships proposed between antecedent, error, and the event under consideration met standards of acceptability. These were (1) would the error have occurred if the antecedents that preceded it had not been present and (2) would the accident have occurred if the error that preceded it had not been committed? As an additional check, three criteria were proposed to determine the value of relationships between antecedents and errors. These require the relationships to be simple, logical, and superior to other possible relationships. In this accident the answers to the counterfactual questions are clear, had the crew monitored the airspeed the accident would not have occurred, and had the antecedents cited not been present, the crew would have monitored the airspeed and hence would have recognized, in time to avoid the accident, that it was deteriorating and needed to be increased. The relationships between antecedents and error, moreover, meet investigative standards of logic, simplicity, and superiority to other explanations for the error.

Terminating the Search for Antecedents

Chapter 3 also addressed the stopping point at which the search for antecedents should be stopped. One can go back seemingly indefinitely to

antecedents that may have influenced the errors, but at some point one would reach a point of diminishing returns and the additional search would not be worth the effort. In this accident, that search terminated at the manufacturer and the airline. Searching for antecedents beyond these would have diluted the importance of the antecedents that are closest to the critical errors leading to the accident.

Recommendations

Investigators issued 21 recommendations to address deficiencies they identified in this accident. Some addressed shortcomings regarding airport fire and rescue capabilities, but 12 of the recommendations addressed crew performance with a highly automated airplane and the antecendents to error discussed presently. The recommendations, which were directed to the Federal Aviation Administration, the airline, and the airplane's manufacturer, can be seen to address each of the antecedents cited, except for the pilots' workload. That was already addressed by the airline's requirement for their pilots to discontinue approaches that are not stabilized. Among other recommendations, investigators asked the Federal Aviation Administration to (National Transportation Safety Board, 2014):

> Require Boeing to develop enhanced 777 training that will improve flight crew understanding of autothrottle modes and automatic activation system logic through improved documentation, courseware, and instructor training.
>
> Once the enhanced Boeing 777 training has been developed, as requested in…[the previous recommendation], require operators and training providers to provide this training to 777 pilots.
>
> Require Boeing to revise its 777 Flight Crew Training Manual stall protection demonstration to include an explanation and demonstration of the circumstances in which the autothrottle does not provide low speed protection.
>
> Once the revision to the Boeing 777 Flight Crew Training Manual has been completed, as requested in…[the previous recommendation], require operators and training providers to incorporate the revised stall protection demonstration in their training.
>
> Convene an expert panel (including members with expertise in human factors, training, and flight operations) to evaluate methods for training flight crews to understand the functionality of automated systems for flightpath management, identify the most effective training methods, and revise training guidance for operators in this area.
>
> Convene a special certification design review of how the Boeing 777 automatic flight control system controls airspeed and use the results

> of that evaluation to develop guidance that will help manufacturers improve the intuitiveness of existing and future interfaces between flight crews and autoflight systems.
>
> Task a panel of human factors, aviation operations, and aircraft design specialists, such as the Avionics Systems Harmonization Working Group, to develop design requirements for context-dependent low energy alerting systems for airplanes engaged in commercial operations. (p. 130)

Investigators also asked the airline to

> Revise your flight instructor operating experience (OE) qualification criteria to ensure that all instructor candidates are supervised and observed by a more experienced instructor during OE or line training until the new instructor demonstrates proficiency in the instructor role.
>
> Issue guidance in the Boeing 777 Pilot Operating Manual that after disconnecting the autopilot on a visual approach, if flight director guidance is not being followed, both flight director switches should be turned off.
>
> Modify your automation policy to provide for more manual flight, both in training and in line operations, to improve pilot proficiency. (pp. 131–132)

Investigators asked the manufacturer to

> Revise the Boeing 777 Flight Crew Operating Manual to include a specific statement that when the autopilot is off and both flight director switches are turned off, the autothrottle mode goes to speed (SPD) mode and maintains the mode control panel-selected speed.
>
> Using the guidance developed by the low energy alerting system panel created in accordance with… [a recommendation issued as a result of this accident] develop and evaluate a modification to Boeing wide-body automatic flight control systems to help ensure that the aircraft energy state remains at or above the minimum desired energy condition during any portion of the flight. (p. 132)

Summary

This accident illustrates how antecedents that individually would likely not have led to error, interacted during the final approach and attempted landing, to lead the operators to commit a fundamental piloting error. All pilots, from the beginning of their flying careers, are taught to monitor their airspeed, yet these pilots failed to do so through the most critical flight operational phases, approach and landing.

They created the circumstances that allowed the antecedents to interact and affect their performance by failing to simultaneously stabilize both the airplane's airspeed and vertical speed during the approach so that one or the other was outside of acceptable operating range throughout the approach. Their efforts to stabilize both flight parameters in the decreasing available time until landing increased their workload to the point that they were unable to devote the effort needed to monitor critical aspects of the approach.

As a result of the design of the airplane's display, in which only visual information about the autothrottle operating mode change was presented, the pilots failed to notice that the autothrottle had changed modes independent of any direct action on their part. An aural alert signaling the change would likely have caught their attention in a way that the visual presentation, in the high workload environment, did not.

The crew's lack of awareness of the mode change was exacerbated by the manufacturer's failure to inform its operators that this airplane allowed that particular autothrottle operating mode, the mode that the autothrottle itself engaged when the pilot flying briefly moved the thrust levers to flight idle, to disengage itself from speed control.

The pilots' lack of awareness of (1) the change in autothrottle mode and (2) the effects of that change on airspeed control, was exacerbated by their respective inexperience, the pilot flying in executing nonprecision approaches in this airplane and the pilot monitoring in observing the performance of B-777 pilots. Together, their inexperience contributed to their errors. Further, their fatigue contributed to degradation in their monitoring of critical flight parameters, a monitoring that was already compromised by the high workload the pilots had created for that phase of flight.

Finally, the pilots' expectations regarding speed control and their manual flying performance were adversely affected by the airline's training and policies. They were led to believe that the autothrottle would not allow airplane speed to deteriorate to an unsafe level, and they were encouraged to rely exclusively on the airplane's automation for flight and airspeed control throughout the different phases of flight. They failed to notice, in time to avoid the accident, that they needed to control airspeed manually.

References

Bainbridge, L. 1983. Ironies of automation. *Automatica*, 19, 775–779.

Dutch Safety Board. 2010. *Crashed during approach, Boeing 737-800, near Amsterdam Schiphol Airport, 25 February 2009*. The Hague: Dutch Safety Board.

National Transportation Safety Board. 1984. *Aircraft accident report, Scandinavian Airlines System, Flight 901, McDonnell Douglas DC-10-30, John F. Kennedy International Airport, Jamaica, New York, February 28, 1984*. Report Number AAR-84/15. Washington, DC: National Transportation Safety Board.

National Transportation Safety Board. 2014. *Aircraft Accident Report, Descent below Visual Glidepath and Impact with Seawall, Asiana Airlines Flight 214, Boeing 777-200ER, HL7742, San Francisco, California, July 6, 2013*. Report Number AAR-14/01. Washington, DC: National Transportation Safety Board.

Lenne, M. G., Triggs, T. J., and Redman, J. R. 1997. Time of day variations in driving performance. *Accident Analysis and Prevention*, 29, 431–437.

17

Final Thoughts

Most investigations are carried out after an event has occurred. But the search to reduce opportunities for error should be ongoing, even in the absence of an accident. System managers, administrators, operators, regulators, and others involved in operating complex systems need to be vigilant in the search for system deficiencies that could lead to errors and accidents. The potential for unknown and unrecognized antecedents to error residing in systems is too great to allow regulators, companies, and operators to become complacent about the safety of their systems. Avoiding such views and remaining on guard to identify and mitigate error antecedents is proactive and in the best interests of safety.

Given the daily pressures of those involved in system operations, one could be expected to encounter difficulties conducting proactive investigations in the absence of an incident or accident (e.g., Carroll, Rudolph, Hatakenaka, Wiederhold, and Boldrini, 2001). Few operators, managers, or regulators have the time available for the data gathering and analysis activities that are needed to recognize and suggest remediation strategies to reduce system deficiencies and vulnerabilities.

Reason (1997) offers several techniques to improve the "safety culture" of complex systems. He argues that safety cultures are designed to reduce opportunities for error in complex systems, and actions can be taken before the fact to improve the safety of many aspects of system operations, from maintenance, to regulation, to daily operations, if the necessary data have been collected and disseminated. As he writes,

> In the absence of bad outcomes, the best way—perhaps the only way—to sustain a state of intelligent and respectful wariness is to gather the right kinds of data. This means creating a safety information system that collects, analyses and disseminates information from incidents and near misses as well as from regular proactive checks on the system's vital signs. All of these activities can be said to make up an informed culture—one in which those who manage and operate the system have current knowledge about the human, technical, organizational and environmental factors that determine the safety of the system as a whole. In most important respects, an informed culture is a safety culture. (p. 195)

Strauch (2015), by contrast, distinguishes between organizational errors and individual operator errors, and provides guidance to investigators to identify and investigate the role of antecedents to organizational errors.

Companies that were aware of operational deficiencies and did not take action to address them, or companies that, because of the nature of the organizational shortcomings should have addressed them but did not, will have committed organizational errors and thus can be considered to have caused or contributed to the cause of the errors that their operators have committed.

While it may be difficult for companies to acknowledge that their actions or inactions led to errors that caused accidents, such acknowledgement is necessary for safe operation. Only by clear, objective, and systematic data gathering efforts, irrespective of where the data lead, can companies learn from their own errors and implement meaningful measures to enhance safety. Managers, administrators, regulators, and others hoping to obtain "the right kinds of data" can accomplish this in several ways. Reason suggests developing and implementing a self-reporting system in which employees can report safety deficiencies in a non-punitive environment. A self-reporting system should encourage learning about safety deficiencies and security vulnerabilities before they lead to potentially severe consequences. Companies can also conduct proactive investigations in response to minor events. These investigations may highlight previously unknown safety-related information, and improve investigative skills as well.

Investigative Proficiency

Conducting safety reviews and proactive investigations also help maintain and enhance investigative proficiency, as well as providing information to enhance safety. The environment in which proactive incident investigations are conducted, in the absence of a major event, is also likely to be free of the stresses that often follow major events, and therefore, likely to be a supportive environment for novice investigators. Investigative skill is like any other, the more one can practice it, the better one will be when needed to exercise those skills.

Criteria

Because of routine operational needs, managers and administrators may be reluctant to divert potentially valuable resources from operational duties to conduct incident investigations, despite the likely long-term safety benefits from conducting investigations. Rather, they may instead focus on the personnel and resource expenditures needed to conduct proactive investigations.

Investigators can help managers and administrators select events that warrant investigations by developing criteria with which to evaluate the need for

proactive investigations. The criteria that follow are applicable to nearly all complex systems:

- Type and frequency of previous operator errors committed and severity of their consequences
- Frequency and severity of recent incidents
- Interval since most recent investigation
- Amount and value of available system safety data
- Value of potential lessons learned

The greater the number of operator errors in the incident, the more serious their consequences, the more frequent the recent incidents, and the lower the amount and value of available system safety data available, the more an investigation is warranted.

An incident in which many errors were committed has a greater need for investigation than one with just a few. A system that has experienced a relatively high number of recent incidents also would benefit from proactive investigation. These suggest the presence of safety deficiencies that could otherwise lead to a major accident, and that could lead to effective recommendations to address the deficiencies. On the other hand, a system that already collects a substantial amount of available safety data may not benefit as much from a proactive investigation as would one with less data. In those instances, the cost of collecting additional safety-related data may not be outweighed by the potential benefits, assuming the data provide information about the presence of known system safety deficiencies.

Models of Error, Investigations, and Research

Moray (1994, 2000) and Reason's (1990, 1997) models of error have guided much of the process outlined in this text. These models have had considerable value in helping understand error, and substantial influence on the insights of students of error. Both have helped bridge the gap that often exists between theories and their application to error investigations.

Models help researchers and investigators understand the data they have gathered, the contribution of the data to the overall investigation, and they serve to guide investigators' analytical efforts. However, as models guide, models can also hinder, if investigators rigidly adhere to them to the detriment of other, more applicable investigative approaches. No single error model is equally applicable to all circumstances; each may have shortcomings that are unique to particular circumstances.

As with empirical research, one needs to follow what the data describe rather than the models or theories used to explain them. This means that investigations should allow the data to determine the relationships between antecedents and errors and relationships between errors and the events under investigation. Assuming that investigators have obtained the needed data, apply the model or theory that best explains the relationships of interest to the investigation. Although this text has adopted Moray and Reason's models to illustrate investigative technique and methodology, others may be better suited to the needs of an investigation. So long as the fundamental rules of investigative logic are followed, the derived relationships and explanations will be sound.

Research and Investigations

Both research studies and accident investigations can provide data that explain behavior in complex systems. For example, as discussed, the extensive research that has been conducted on decision making in "real world" dynamic environments has led to findings that are directly relevant to the investigations of many events, helping investigators understand the nature of the operator decisions and thus assisting in the development of remediation strategies to prevent similar occurrences. Information from accident investigations has also helped to focus research needs and activities by revealing operator actions in real world settings. Knowing the results of both research and investigations of similar accidents and incidents can assist both the researcher and the investigator to better understand the issues being examined in the particular investigation.

However, investigators may encounter events where few relevant research studies and investigations have been conducted. Circumstances in which relatively unexplored issues play major roles in accidents occasionally occur and, while the efforts to investigate them may be considerable, the derived information may have substantial value to a variety of settings. For example, investigators of the 1996 explosion of the Boeing 747 over Long Island (National Transportation Safety Board, 2000), focused on a rarely encountered scenario, an in-flight explosion caused by fuel tank vapors that had ignited, on which little pertinent information was available. Much of the information obtained in that investigation was applied to aircraft design and aircraft certification, going a long way to enhancing safety by making this event highly unlikely in the future.

Investigators conducted original research to obtain fundamental information regarding fuel volatility and ignition sources to understand the phenomenon. Although it is rare for researchers to conduct original research in the context of an accident investigation, the needs of the investigation may require that. In the investigation of that Boeing 747 accident, the information obtained from the investigation will help aircraft designers, regulators, and the aviation industry improve aviation safety for years to come.

Quick Solutions

Operators, managers, regulators—as well as investigators—may seek quick or facile solutions to address a recognized safety deficiency or vulnerability. Frequently, quick solutions are needed and appropriate. However, the complexity of modern systems and the relationships among antecedents and errors within them often call for complex and time consuming solutions to provide effective mitigation techniques. Those involved in system operations need to be prepared to implement long-term, potentially difficult strategies to improve system safety. The methods may be expensive and/or difficult to implement, but the objective of improving system safety will warrant it.

Conclusions

When beginning an investigation the task may seem arduous, and the frustrations overwhelming, but the benefits to be gained from systematic and thorough investigations will make the effort worthwhile. One has only to examine the steady improvements in system safety to appreciate the benefits to be gained. For example, aircraft accidents today are so rare that only a handful of major accidents occur each year, worldwide. Twenty years ago, for example, it seemed that the same number of aircraft accidents that occur in a year today would occur in a month, despite the considerable increase in worldwide flight operations since then.

The potential for human error will not be eliminated. However, investigators have demonstrated that opportunities for error can be effectively reduced. Complex systems are likely to increase in their complexity and, as Perrow (1999) has argued, this will increase the likelihood of "normal accidents." But even Perrow would argue that applying the lessons of error investigations reduces their likelihood. The objective of this text has been to provide the knowledge and skills investigators need to accomplish this. The benefits of doing so will continue to make the efforts worthwhile.

References

Carroll, J. S., Rudolph, J. W., Hatakenaka, S., Wiederhold, T. L., and Boldrini, M. 2001. Learning in the context of incident investigation: Team diagnoses and organizational decisions at four nuclear power plants. In E. Salas and G. Klein (Eds.). *Learning expertise and naturalistic decision making* (pp. 349–365). Mahwah, NJ: Erlbaum.

Moray, N. 1994. Error reduction as a systems problem. In M. S. Bogner (Ed.), *Human error in medicine* (pp. 67–91). Hillsdale, NJ: Erlbaum.

Moray, N. 2000. Culture, politics and ergonomics. *Ergonomics*, 43, 858–868.

National Transportation Safety Board. 2000. *In-flight breakup over the Atlantic Ocean, Trans World Airlines flight 800, Boeing 747-131, N93119, near East Moriches, New York, July 17, 1996*. Report Number AAR-00-03. Washington, DC.

Perrow, C. 1999. *Normal accidents: Living with high-risk technologies* (2nd ed.). Princeton, NJ: Princeton University Press.

Reason, J. T. 1990. *Human error*. NY: Cambridge University Press.

Reason, J. T. 1997. *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.

Strauch, B. 2015. Can we examine safety culture in accident investigations, or should we? *Safety Science*, 77, 102–111.

Index